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exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machinery

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na temat

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Gdańsk, 24 - 27 września 1974 r.

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IIIrd SCIENTIFIC CONFERENCE

on

STEAM TURBINES OF GREAT OUTPUT

Gdańsk, September 24 - 27, 1974

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III НАУЧНАЯ КОНФЕРЕНЦИЯ

на тему

ПАРОВЫЕ ТУРБИНЫ БОЛЬШОЙ МОЩНОСТИ

Гданьск, 24 - 27 сентября 1974 г.

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Instrument for Measuring Diameter and Number of Water Droplets in Steam

Introduction

When investigating the thermodynamic and transport phenomena in wet steam it is necessary to known the sizes and number of liquid phase droplets. This is important for modelling the phenomena which occur during the operation of the actual steam turbines in which some part of the stages operates with a two-phase medium. This especially concerns the turbines operating in connection with the pressurized water reactors where most of the stages are running in wet steam. Water droplets produced in the process of a spontaneous condensation are called the primary droplets. They have small diameters of about $1 \cdot 10^{-7}$ m. There exist also the larger, so called secondary droplets with diameters of 10^{-6} up to 10^{-4} m, which originate due to the disintegration of the fluid film on the surfaces of the turbine parts swept by wet steam.

Various measuring methods are used to measure diameters and number of these droplets. These methods are functionally based on the location of some probe in the flow of a two-phase medium. This is sometimes rather complicated. Moreover, the probes affect the local flow conditions. It is, therefore, desirable to use a contactless measuring method and such method should also be suitable for performing the spot measurings, which is important when selecting the size distribution of these droplets in a certain cross-section. Optical measuring methods are based on an interaction of a defined light wave with a two-phase medium and have the properties of contactless measuring methods with wide information capacity: these methods utilize the fact of light scattering on particles having different optical properties in a optically transparent medium. The method described here was used by Šifrin [1] and others [2] and applied especially in the colloid chemistry and meteorology and lately even in the steam turbine research. The electromagnetic theory of light scattering on transparent particles was elaborated by Rayleigh, Love, Mie and Debye [3]; the results of this theory were tested in experiments. The opto-electrical instrument described below has been based on the experience gained from the mentioned theories and tested in measurements of the parameters of water droplets by means of a photometry process. The design of the instrument allows tests and runs in a trial operation.

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Measuring method theory

When passing a plane wave of monochromatic light through a layer of an optically transparent medium with monodispersion, optically homogeneous particles, the intensity of the light passing through the layer is determined by the Lambert-Beer's law

$$I=I_0 \exp(-Kl), \tag{1}$$

where I – the intensity of light passing through the layer, I_0 denotes the intensity of light incident on the layer, l denotes the thickness of the layer in the direction of the light wave propagation, K denotes the attenuation coefficient; this coefficient is then determined from relation

$$K=\pi r^2 NQ, \tag{2}$$

where r denotes the radius of particles, N denotes the number of particles in a volume unit, Q denotes the extinction coefficient which is the function of both the light wave-length λ' in the measuring medium and the r/λ' ratio. Q can be expressed generally by the function

$$Q=f(n)\,\varphi(\alpha),$$

where n means the refraction index of environment, in some cases the complex refraction index; parameter $\alpha=2\pi r/\lambda'$. Function $\varphi(\alpha)$ was determined by Rayleigh-Gansen and has the form of a polynom, see example in [2].

The Lambert-Beer's law in the form used more often

$$\ln \frac{I_0}{I}=Q\pi r^2 N\,l \tag{3}$$

or

$$\log \frac{I_0}{I}=\frac{Q\pi r^2 N\,l}{2.3} \tag{4}$$

is obtained by taking the logarithm of eq. (1).

The value of the extinction coefficient Q in eqs. (3) or (4) can be either calculated or obtained as well on the basis of experiments; the performed experiments proved that the theoretically calculated values are correct. In the literature we usually find the values of Q as depending on the dimensionless parameter α.

If we perform the measuring of the light intensity attenuation e.g. with two wave lengths we receive the relations

$$\ln \frac{I_{01}}{I_1}=Q_1\,\pi r^2 Nl, \quad \ln \frac{I_{02}}{I_2}=Q_2\,\pi r^2 Nl. \tag{5}$$

The value of the extinction coefficients ratio may be determined from eq. (5); it is equal to:

$$\frac{Q_1(\lambda_1, \alpha_1)}{Q_2(\lambda_2, \alpha_2)}=\frac{\ln I_{01}-\ln I_1}{\ln I_{02}-\ln I_2}. \tag{6}$$

Eq. (6) can be transformed into

$$\ln Q_1(\lambda_1, \alpha_1) - \ln Q_2(\lambda_2, \alpha_2) = \ln \frac{\ln I_{01} - \ln I_1}{\ln I_{02} - \ln I_2}. \tag{7}$$

For the actual measurements i.e. for a certain value of the particle radius r we may write the following relation for the dimensionless parameter

$$\frac{\alpha_1}{\alpha_2} = \frac{\lambda_2}{\lambda_1}. \tag{8}$$

When combining eqs. (6) and (8) we then receive

$$\frac{\ln \dfrac{Q_1(\lambda_1, \alpha_1)}{Q_2(\lambda_2, \alpha_2)}}{\ln \dfrac{\lambda_2}{\lambda_1}} = \frac{a}{b} \equiv x. \tag{9}$$

Equation (9) determines the slope of the secant to the curve of function $\ln Q = Q(\alpha)$ passing through the points corresponding to values α_1, α_2; in the direction of the ordinate these points are in pitches a and in the direction of the abscissa in pitches b. The question now is to localize these points of the function $Q(\alpha)$. If we use the Legendre's lemma on the mean value, generally defined by relations

$$f(x_0) = f(x_1) + \vartheta[f(x_2), f(x_1)] \quad \text{for} \quad 0 \leqslant \vartheta < 1 \quad \text{and} \quad f(x_1) > f(x_2)$$

which is valid under the assumption that the function $f(x)$ is continuous and monotonous between the values $f(x_1)$ and $f(x_2)$ i.e. does not have a local extreme and is not constant, we can determine the value of an internal point α_0 from the expression

$$\ln \alpha_0 = \ln \alpha_1 + \vartheta \left(\ln \frac{\lambda_2}{\lambda_1} \right), \qquad \vartheta = 0.5. \tag{10}$$

Then a condition can be set for the point α_0 to the effect that the slope of the secant to the curve $Q(\alpha)$ at this point has the same value as the slope of the secant according to eq. (9). Under such assumptions we can determine this value and by means of it also the values of parameters α_1, α_2

$$\begin{aligned} \ln \alpha_1 &= \ln \alpha_0 - \vartheta(\ln \lambda_2/\lambda_1) \\ \ln \alpha_2 &= \ln \alpha_0 + \vartheta(\ln \lambda_2/\lambda_1) \end{aligned} \qquad \vartheta = 0.5. \tag{11}$$

We will find the values $Q(\alpha)$ for them by means of the tables or diagram of function $Q_1(\alpha_1)$, $Q(\alpha_2)$. The accuracy of these values can be checked by performing a check calculation according to eq. (6). For the known values λ we determine r of the particles by a calculation utilizing α_1, α_2, and in checking – even α_0. If we know the value of the particle radius r we calculate the number of particles from the equation

$$N=\frac{\ln I_{01}-\ln I_1}{Q_1\,\pi r^2 l}=\frac{\ln I_{02}-\ln I_2}{Q_2\,\pi r^2 l}\,. \tag{12}$$

The application of the described measuring method is based on the knowledge of the function $Q=Q(\alpha)$ or $Q/r=f(r)$ for certain values of the wave length and certain medium. In this sense the facts can be supported by the available literature data; for the actual measuring it is, however, more advantageous to calculate values $Q=Q(\alpha)$ according to the theoretical relations for this function, see e.g. ref. [4].

In this paper we will only illustrate the described measuring method by the statement that with the application of the monochromatic light of $\lambda\sim0.5$ μm the parameter α will have the approximate value of 1.25 i.e. in this case we will be in the region of monotonous

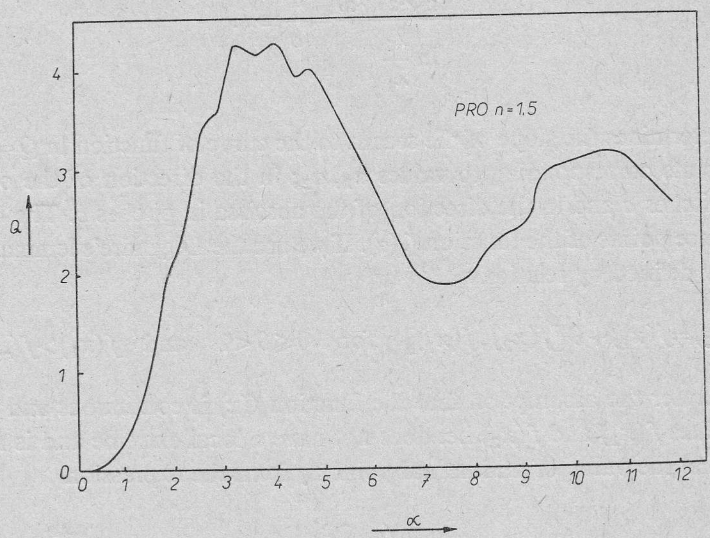

Fig. 1. Diagram of $Q=f(\alpha)$

change of the function $Q=Q(\alpha)$. Fig. 1 taken from ref. [5] shows that Q/r for the given wavelength is the monotonous function up to diameter of droplets of about $2\cdot10^{-6}$ m. This means that the mentioned measuring method is suitable mainly for measuring primary water droplets diameters.

Measuring instrument description

For the earliest verification of the above mentioned measuring method we have designed in the National Research Institute for Machine Design an opto-electrical instrument. This instrument was a reconstructed Schlieren apparatus of Messrs. Carl Zeiss, Jena in GDR. The diagram of this apparatus is shown in Fig. 2; block diagram of the apparatus is presented in Fig. 3. The following is evident from the optical diagram: the light source is HBO 500 high pressure mercury vapor lamp. Light interference filters may be changed at the spot of the light source condenser outlet gap i.e. at the place of the effective light source, so that we obtain the monochromatic light with wave lengths 545, 576 and 426 nm. Part of the light beam is deflected by a prism to the aperture of the reference photomultiplier before the beam enters into the measuring space. Light which passes through the measuring space goes to the aperture of the other photomultiplier. The light beam in the measuring space may be checked by means of a visual device i.e. on the focusing screen. Rotary polarizers are placed in front of the both photomultipliers so that we can adapt the intensity of light coming on their gaps to prevent overloading of the photomultipliers.

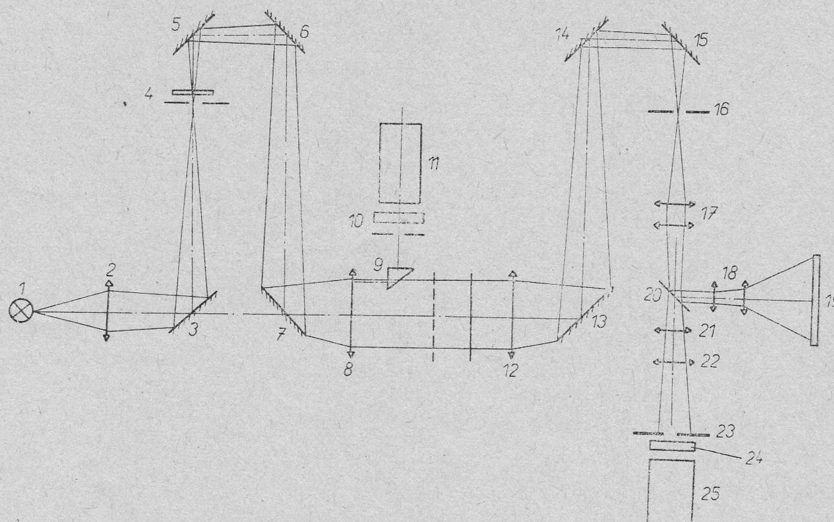

Fig. 2. Optical diagram of the apparatus
1 – light source, HBO 500, *2* – condensor, *3, 5, 6, 7, 13, 14, 15* – mirrors, *4* – source gape, *8, 12, 17, 18, 21, 22* – objectives, *9* – prism, *10, 24* – polarizers, *11, 25* – photomultipliers, *16* – gap, *20* – deflecting moving mirror, *19* – screen, *23* – measuring gap

tipliers. The detection is of the point type, by means of the gap which may be traversed over the whole cross-section of the light beam. Moreover, the whole apparatus may travell crosswise to the measuring space.

As to the block diagram in Fig. 3 it is necessary to point out the following: due to the alternating operation of the high pressure vapor discharge lamp which is excited by AC current with the mains frequency, the output electric signals of the both photomultipliers can be amplified and measured by AC vacuum-tube voltmeters. Besides the measuring of the values of these signals by vacuum-tube voltmeters they can by also measured by a vacuum-tube digital voltmeter consisting of TESLA BM 480 potential-frequency converter and TESLA BM 445 scaler. Finally, even a digital record of the measured values can be obtained with the aid of a TESLA BM 4450 rapid printer and CONSUL 1×P 832 27 typewriter. An oscilloscope serves as the checking instrument of the apparatus. Switching box and remote control device for changing the interference filters, including auxiliary electric sources, form the parts of the apparatus.

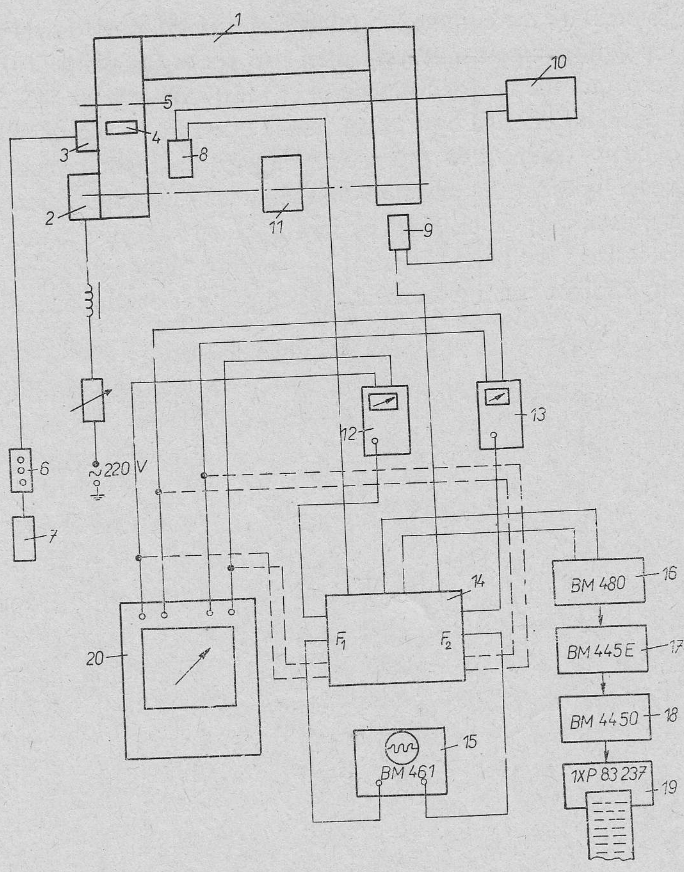

Fig. 3. Block diagram of the device
1 – schlieren-apparatus, *2* – light source, *3, 6, 7* – remote controle of filters, *4* – filters, *5* – source gap, *8* – reference photomultiplier, *9* – measuring photomultiplier, *11* – measuring space, *10* – supply for photomultipliers, *12, 13* – AC – tube voltmeter, *14* – switching box, *15* – cathode oscilloscope, *20* – ratio measuring device

Origins of measuring errors

Errors which may effect the measurement results can be divided into two main groups:

1) errors due to inaccurate measurements of values I_0, I_1 and to the instability of the whole opto-electric instrument,

2) errors due to the features of the investigated system i.e. due to an incomplete mono-dispersion or polydispersion of the particles in the two-phase medium and neglecting of multiple dispersion of light on the particles when their concentration is higher.

The influence of the droplet polydispersion can be basically investigated by comparing the attenuation coefficient K as given by eq. (2) and by the relation

$$K = N\pi \int_{r_{\min}}^{r_{\max}} Q(r) f(r) r^2 dr \tag{13}$$

which is valid for the polydispersion system. As far as $Q/r < 1$ the systems are equal regardless the degree of polydispersion; this was found out in experiments by Van Hulst [7]. In case of steam the values of function Q/r will be $Q/r \sim 0.1$ and, therefore, Van Hulst's assumption should be fulfilled. The latter relation may be still adapted to

$$K = N\pi Q \int_{r_{min}}^{r_{max}} f(r)\, r^2 dr \tag{14}$$

and then the equation for the photometrically equivalent monodispersion system can be written:

$$r^2 = r_F = \int_{r_{min}}^{r_{max}} f(r)\, r^2 dr \tag{15}$$

which shows that the total cross-section of droplets in the unit volume decides on the photometrical properties of the polydispersion system. For the determination of the mean value of droplets radius it would be necessary to find out the distribution of droplet density according to their radii in experiments with another independent measuring method and then to compare the both measurements.

Multiple light dispersion occurs when the concentration of droplets reaches higher values: according to ref. [7] this takes place when $I_i/I_0 > 0.74$. This fact may be proved only in an experiment. One of the possible ways is to compare the measured values with the values calculated theoretically according to the Lambert-Beer's law.

Errors of the measuring instrument depend on its adjustment and on the measuring process. This problem is not dealt with in this paper.

Results of instrument tests

After the assembly of the described opto-electric instrument its functioning has been to ascertain the decisive properties of some of its parts.

The first important property is the linearity of the photomultiplier responses. The latter was checked in such a way that we inserted an adjustable circular orifice plate into the measuring space and then centred its image to the gap of photomultipliers. The position of the orifice plate was simultaneously marked on the focusing screen of the instrument checking section. Then we moved an optical wedge of known parameters at the place of the orifice plate: the ORWO E4-7190 wedge was used. In this way we found out that under given instrument parameters the responses of the photomultipliers are linear; this was true within a wider extent than expected from the changes of the light intensity during the measuring.

Another value which interested us was the distribution of the light intensity along the whole cross-section of the light beam in the instrument: this was checked by means of a cross support of the other photomultiplier which measured the light intensity at various points of the light beam cross-section. We ascertained that, with the exception of the beam part just at the margin, the distribution of the light intensity was uniform.

It is important also to know the time stability of the light source. It was proved that the mentioned HBO 500 high pressure mercury vapor lamp is not ideal for this purpose neither in DC nor AC operation. The time changes of its light intensity are observed in form of su-

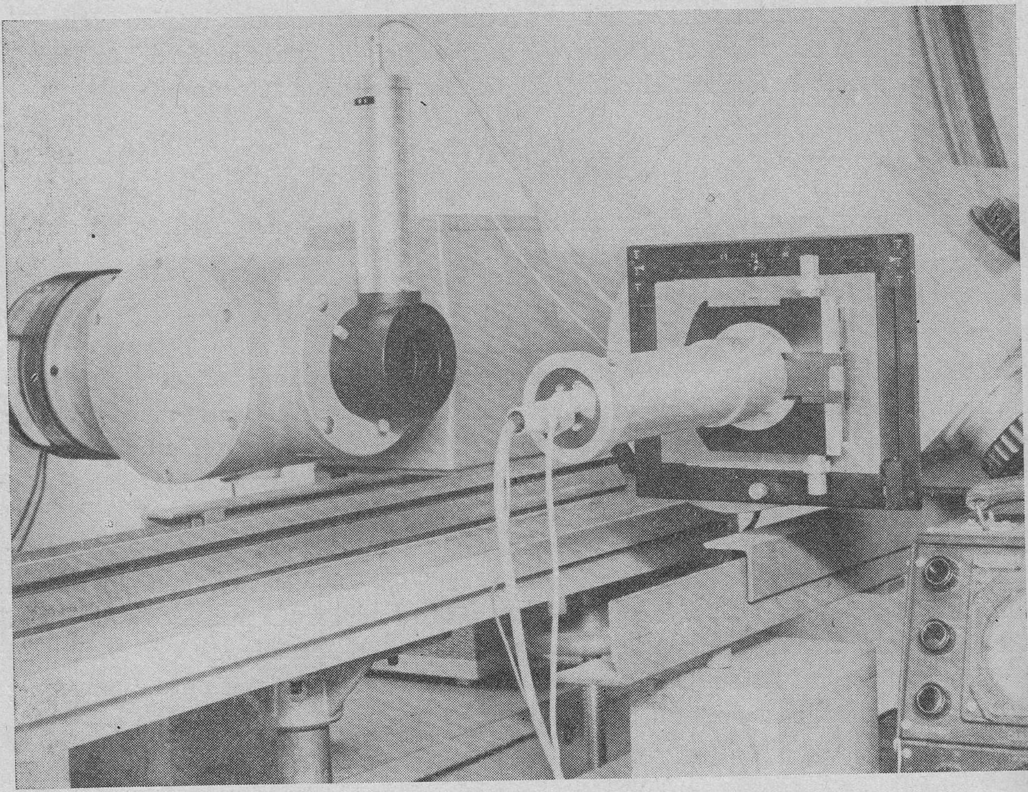

Fig. 4. Photography of the apparatus

dden steps by about 30% in maximum, both in short and long periods. We think that this behaviour of the mentioned lamp is caused by the geometrical dimensions of its arc which is too long and, therefore, also unstable in space. This causes the deflection of the arc from the condenser focus plane and results in the stochastic changes in the light intensity of the effective light source.

The measured fluctuation of the light intensity might be, naturally, even an apparent one i.e. due to an instability of the multiplier; with regard to its operating conditions and with its feeding from HT stabilized source such contingency has been practically eliminated. To reduce the influence of the vapor discharge lamp on the results of the measurements we consider to use a smaller HB 50 high pressure vapor discharge lamp in the future as this lamp has a shorter and, therefore, more stable discharge in the space.

The influence of the light source intensity on the results of the measurements can be theoretically eliminated by an instantaneous measuring of the ratios of both light intensities i.e. output electric signals of both photomultipliers by means of a ratio measuring device; naturally, it is necessary to know the possible potential dependence of this device or to ascertain it by gauging.

We performed the function verification tests of the apparatus in December 1973; according to these tests the opto-electric instrument fulfilled the functions expected from it. In 1974 we shall start with the measuring of sulphuric sols; the sols processed according to the

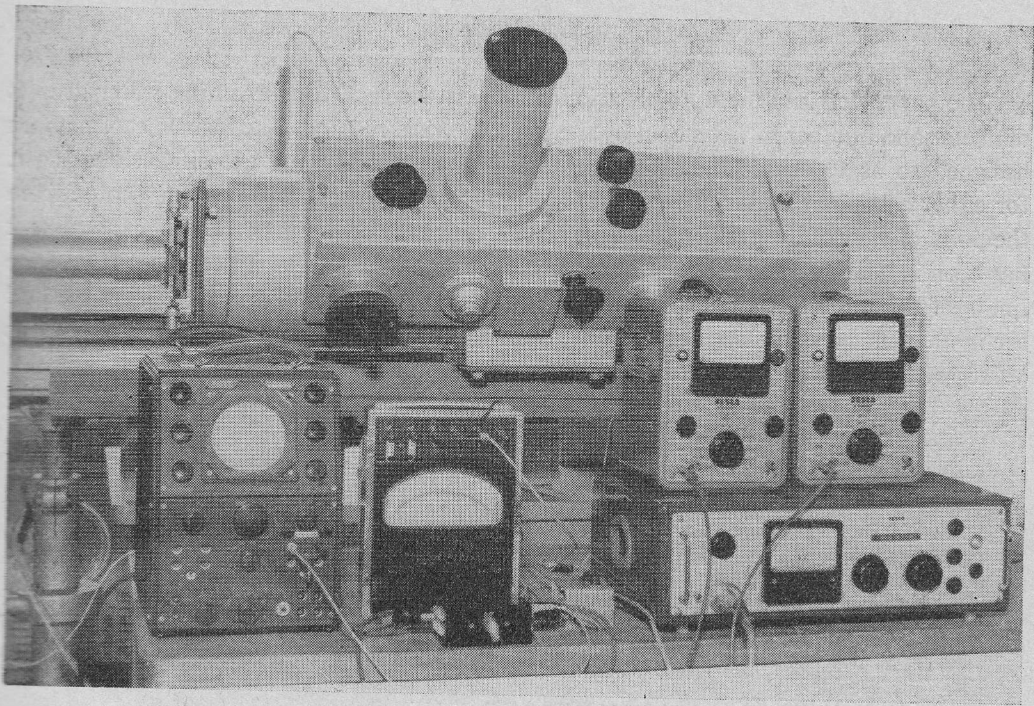

Fig. 5. Photography of the device

following reaction are concerned

$$Na_2 S_2 O_3 + H_2 SO_4 \Rightarrow S + SO_2 + SO_4^{-2} + H_2 O + 2Na$$

Sulphur is in the shape of droplets in these emulsions; titration may be applied for the indication of the concentration and quantity of sulphur released in the shape of droplets after a certain time of reaction duration and from relation

$$\frac{\bar{Q}}{r} = \frac{4}{3} \frac{\rho_S \ln (I_0 / I_i)}{c_S l}, \tag{16}$$

where c_S means sulphur concentration, ρ_S means sulphur specific mass, l means the depth of the measuring cell, for certain values of light intensity ratios (measured) the diameters of sulphur particles can be determined in checking for the theoretically calculated values of function $\bar{Q}/r = f(\lambda')$. The value calculated in this way may be then compared with the value ascertained only on the basis of the photometric measurements. The significance of the instrument tests with the sulphur sols is in the size of the sulphur particles which change within 24 - 30 hours. Practically the sols are monodispersive so that the extent of applicability of the photometric method can be found out of them as far as the dimensions of the particles are concerned [7].

As soon as the experimental steam tunnel will be put into operation and we shall already have certain experience with the operation of the described opto-electrical device, we will perform measurements in steam. Even here it is possible to perform the check measurement of droplet diameters by the method which is given in ref. [7].

Conclusion

The paper decribes the opto-electric instrument designed for measuring water droplet diameter and number in wet steam by the photometrical method. The instrument has been designed so as to enable the point measuring in a channel with two-dimensional flow, for either a laminar or turbulent flow. The latter measurement will be complicated from the point of view of the evaluation of the results. Since the beginning of 1973 the instrument has been in trial operation for the purpose of investigating its capabilities, especially of the limits of the photoelectric measuring method. The advantages of the measuring method are in its contactless measuring, point measuring and in possibility to obtain instantaneous values of the droplets parameters i.e. instantaneous in space as well in time.

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Przyrząd do pomiaru średnicy i liczby kropel w parze wodnej

Streszczenie

W roku 1973 skonstruowano opto-elektryczny przyrząd służący do pomiaru średnicy i liczby kropel wody w parze mokrej. W urządzeniu tym wykorzystano bezkontaktową fotometryczną metodę pomiaru. Jeżeli przez warstwę ośrodka przezroczystego dla fal świetlnych, zawierającego optycznie jednorodne cząstki rozpraszające, przepuszcza się monochromatyczną falę świetlną, to fala ta jest tłumiona przez cząstki; tłumienie jest funkcją średnicy i liczby cząstek. Przyrząd jest obecnie poddawany próbom. W artykule podaje się teorię działania przyrządu oraz wyniki prób działania.

Прибор дла замера диаметра и количества водяных капель в водяном паре

Резюме

В 1973 году был сконструирован оптиско-электрический прибор для замера диаметра и количества водяных капель во влажном паре. Здесь использован бесконтактный фотометрический метод замера. Если через слой прозрачной для световых волн среды, содержащей оптически однородные рассеивающие частицы, пропускать монохроматическую световую волну, тогда эта волна демпфируется частицами. Демпфирование является функцией диаметра и количества частиц. Прибор актуально подвергается испытаниям. В статье описан принцип действия прибора и предварительные результаты испытаний.