NONCONTACT METHODS OF STUDYING THE PARAMETERS OF PARTICLES IN TWO-PHASE PLASMA FLOWS

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In the last 10-20 years there has been intensive development of a new direction in continuum mechanics — the gasdynamics of multiphase systems. The development of this field of study has been the result both of scientific necessity and important practical applications in atomic energy, rocketry and aviation, chemical engineering, meteorology, and other areas. The literature contains several publications devoted to the gasdynamics of multiphase systems [1-7].

Of great interest is a two-phase plasma—solid-particle system, such systems often being encountered in the processing of powdered raw materials to spheroidize them, in the production of ultradisperse oxides and the synthesis of various compounds, and in spray-coating with a low-temperature plasma. The intensification of processes in plasma chemical reactors and the selection of optimum operating conditions for plasma devices require the development of methods and equipment for determining the parameters of the solid-phase particles at the main stages of the production process [8, 9]. During the short period of time characteristic of plasma chemical processes, the aggregate of solid particles may undergo significant changes with respect to both time and space: there are changes in particle size and shape, the particle-size distribution function, particle concentrations and velocities, particle-velocity and -temperature distribution functions, and the aggregate state of the particles.

The general requirements for methods of analyzing two-phase plasma flows can be stated as follows:

1) assure the necessary measurement accuracy and high resolution with respect to time and space;

2) avoid perturbations of the plasma jets;

3) provide for sufficiently broad ranges of measurements of the main parameters.

DETERMINATION OF THE DISPERSE COMPOSITION AND CONCENTRATION OF SOLID-PHASE PARTICLES IN GAS FLOWS

The experimental methods available for determining the parameters of the disperse phase in a heterogeneous plasma can be divided into contact and noncontact methods. Although contact methods have several disadvantages (the presence of kinetic errors, structural changes in the disperse phase during deposition, complexity of distinguishing submicroscopic particles), they have come into wide use due to their simplicity [4, 10, 11]. The main contact method is deposition of particles of an aerosol sample under the influence of different types of forces (gravitational, centrifugal, inertial, etc.) with subsequent microscopic or photosedimentation determination of the size of the deposited particles. The study [12] investigated suspensions in the jet from a rocket engine by the contact method of collecting a sample. The study [13] used the same method to determine the dimensions and concentration of particles in the flame from combustion of an atomized fuel. The studies [14, 15] used the method of thermoprecipitation to determine the disperse composition of microscopic particles in a gas-dust flow. The work [16] described a method of measuring particle concentration which is based on recording pulses in the collision of particles with a probe inserted into the flow.

It is preferable to use noncontact methods to analyze the disperse phase of a heterogeneous plasma. The holographic method may find wide use, this method allowing the flow to be studied as a whole [17, 18]. The main shortcoming of the holographic method is the com-

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plexity of the experimental setup and of the data analysis. The main advantage of the method over conventional photographic methods is the greater depth of field.

The holographic method and the method of holographic interferometry can be used to determine particle size, countable and bulk particle concentration, particle-size distribution, and particle velocity, temperature, and pressure fields [18].

Either single- or dual-beam schemes can be employed to record holograms of bulk particle distributions. The latter make it possible to obtain sharper images of microscopic objects. Holograms of microparticles are usually obtained in actual optical systems by introducing a lens which makes it possible to construct an enlarged or reduced image of the object near the holographic plate. The use of systems with an enlargement capability in turn makes it possible to use photographic materials with a lower resolving power. Quality holograms permit reproduction of microparticles 3-5 μm in size [9, 18]. According to the literature data, the upper boundary of the microparticle concentration in flows which can be resolved by holographic methods is 10^4-10^5 cm^{-3} [8].

Several works have shown that it is possible to use holography to study the combustion of solid fuels [18, 19] and combustion in experiments with explosive wires [18, 20].

There are certain requirements to be met for using holography to measure microparticle dimensions in a heterogeneous plasma. It was shown in [21] that to obtain a quality hologram the shift in the interference bands during the exposure should not exceed $\lambda/8$.

To study rapidly occurring processes in fast-moving objects, the USSR serially manufactures the UIG-1M pulse-type holographic unit [18]. The unit consists of a single-mode pulsed ruby laser (pulse duration up to 40 nsec, radiant energy up to 0.5 J), an LG-38 helium–neon laser (to establish the image), an OKG-11 helium–neon laser (to adjust the optical elements), and other devices and elements. The specifications of the unit are as follows: size of the objects being recorded (subjects) 20 × 20 × 20 cm, hologram recording time $4 \cdot 10^{-8}$ sec, range of refractive index $2 \cdot 10^{-6}$-$2 \cdot 10^{-3}$. Use of the pulsed laser, with a nanosecond pulse-duration range, does not require protection of the system from vibration. The use of continuous-wave lasers for holography establishes more stringent requirements with regard to providing shock absorption for the holographic instruments (vibration of an individual optical element no greater than hundredths of a micrometer) [18].

The investigations [22, 23] used holographic analysis to analyze heterophase plasma flows. The plasma source here was a 12- to 15-kW plasmatron. The plasma-forming gases were Ar and Ar + N_2 and Ar + H_2 mixtures. Gas consumption was within the range 20-40 liters/min. The investigators studied microparticles of Al_2O_3 measuring 30-100 μm at concentrations of $5 \cdot 10^2$-$5 \cdot 10^3$ cm^{-3}. The measurements were obtained by a dual-beam scheme which made it possible to improve the depth of field (Fig. 1). The radiation source was a ruby laser operated in the Q modulation regime. The generation energy of the laser was 12-15 mJ, with a pulse duration of 30 nsec. In recording holograms on FP-GV2 photographic film, the researchers succeeded in resolving particles as small as 13-14 μm. The use of higher-quality photographic materials in the pulse holography method may make it possible to record particles of 4-5 μm. This work was done at the Institute of Inorganic Chemistry of the Latvian Academy of Sciences.

The use of optical methods involving laser visualization is of considerable interest for analyzing two-phase flows. These methods make it possible to determine parameters such as particle size, concentration, path, and velocity and the microstructure of the gas-density field [6, 24]. The method of high-speed photographic recording of particles in scattered laser radiation [6] makes it possible to determine particle size, path, velocity, and concentration in any section of a two-phase flow. The light "knife" method is used to obtain the record and entails illumination of the subject by a plane-parallel light beam and recording of the radiation scattered by particles. Figure 2 shows the optical system of the unit. The radiation source was a pulsed ruby laser with a pulse duration of 30 nsec and a pulse power of 10^8 W. The method of high-speed photographic recording makes it possible to resolve particles as small as 20 μm, and particles down to 1-2 μm can be resolved with appropriate enlargement and the use of high-resolution photographic materials.

Along with making it possible to record particle dimensions, the impulse schlieren method [6] permits recording of the microstructure of the gas-density fields. Figure 3 presents a diagram of this method. The radiation source is a pulsed ruby laser operating in the Q modulation regime with a pulse energy of 1 J. The recording is done on holographic film. The resolution of the method is 10 μm.

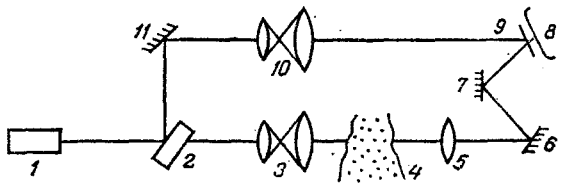

Fig. 1

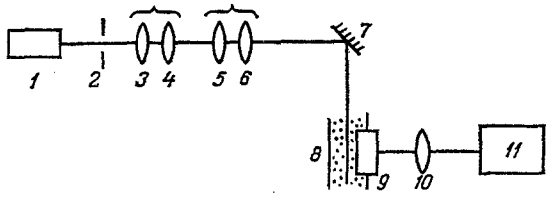

Fig. 2

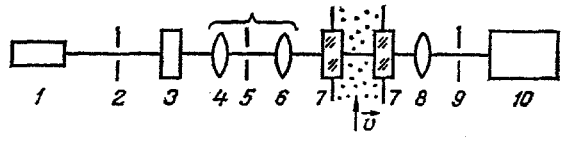

Fig. 3

Fig. 1. Dual-beam holographic system for studying microparticles in a heterogeneous plasma flow: 1) laser; 2) beam splitter; 3, 10) telescopic systems; 4) subject; 5) lens; 6, 7, 11) mirrors; 8) hologram; 9) filters.

Fig. 2. Setup of unit for high-speed photographing of particles in a gas flow: 1) laser; 2) diaphragm; 3, 4) telescopic system; 5, 6) system for forming a plane-parallel beam; 7) mirror; 8) two-phase flow; 9) window; 10) lens; 11) recorder.

Fig. 3. Optical system for impulse schlieren method: 1) laser; 2, 9) diaphragms; 3) attenuator; 4-6) telescopic system; 7) window; 8) lens; 10) photographic detector.

Methods involving laser visualization of multiphase flows are being developed by the Institute of Theoretical and Applied Mechanics of the Siberian branch of the Soviet Academy of Sciences.

Together with methods entailing individual counting of particles, statistical contactless methods have come into wide use (most of these methods are optically based). These methods give information on parameters of the particle-size distribution function [9]. The latter function can be determined within the range 1-300 μm by the method of low-angle light scattering [25]. A survey of light scattering on particles was made in [8, 9]. Thus, we will examine only those methods connected with the radiation of fluorescent objects. The work [26] described a unit for measuring the spectrum of dimensions of drops in a combustion zone. The dimensions of the investigated particles were 3-80 μm.

The studies [27, 28] showed that it is possible to simultaneously determine the bulk and countable concentrations of disperse-phase particles by the method of low-angle scattering. Experiments were performed in a high-temperature flow of products of methane combustion (1900 °C). The range of particle sizes was 7-40 μm, and concentration ranged within $8 \cdot 10^4$-$6 \cdot 10^5$ cm^{-3}. The radiation source was an He—Ne laser. Figure 4 shows a diagram of the unit for determining the disperse composition of a suspension in the flame from combustion of a solid fuel by the method of low-angle scattering [29]. The characteristic dimension of the working volume was 50 μm, while the time resolution was 10^{-3} sec.

Low-angle scattering methods have sufficient time and spatial resolution, but they can be used only under the following conditions [8]: the optical thickness of the object should considerably less than unity so as to eliminate the effect of secondary scattering; the particle sizes should be within the range 1-200 μm; the condition $2\rho(m-1) \gg 1$ must be satisfied, where $\rho = 2\pi r/\lambda$, $m = n/n'n$ is the relative complex refractive index of the material of the particles in relation to the environment. The literature does not contain any information on the use of low-angle scattering methods to analyze dust-bearing plasma flows.

The investigation [30] described new noncontact methods of monitoring the parameters of solid particles in two-phase flows that have been developed by the Dnepropetrovsk Mining Institute and the Stavropol' Polytechnic Institute. Figure 5 shows a system for determining the bulk concentration of SiO_2 particles 52-56 μm in size in a boundary layer by the absorption method. The system of mirrors makes it possible to scan the beam from an LG-52 laser with a minimum interval of 10 μm. The flow-rate concentration of particles was 0.75 kg/kg. Figure 6 shows a system for determining local parameters of two-phase systems — spatial distribution

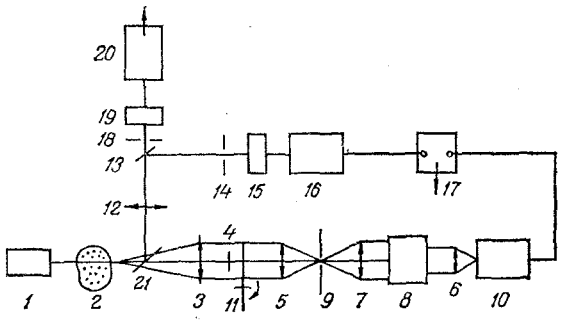

Fig. 4

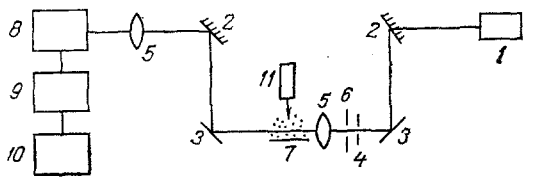

Fig. 5

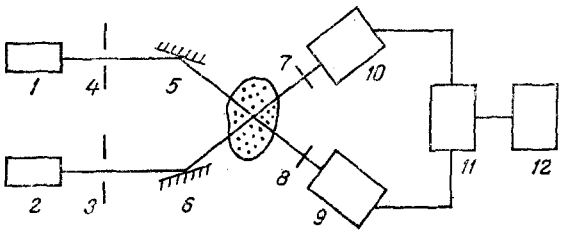

Fig. 6

Fig. 4. Diagram of unit for determining the disperse composition in flames from solid fuel combustion: 1) laser; 2) flame; 3, 5-7, 12) lenses; 4) attenuator; 8) monochromator; 9, 14, 18) slits; 10, 16, 20) photomultipliers; 15, 19) filters; 11) scanning disk; 13, 21) beam splitters; 17) recording oscillograph.

Fig. 5. System for measuring the bulk concentration of solid particles in a boundary layer: 1) LG-52 laser; 2) stationary mirrors; 3) movable mirrors; 4) diaphragm; 5) lens; 6) modulator; 7) plate; 8) AAS-1 atomic absorption spectrometer; 9) digital voltmeter; 10) control panel; 11) LG-56 laser-thickness-gauge.

Fig. 6. Diagram of unit for measuring local parameters of a two-phase flow: 1, 2) LG-75 lasers; 3, 4) diaphragms; 5, 6) mirrors; 7, 8) filters; 9, 10) FÉU-22 photodetectors; 11) S8-2 oscillograph; 12) Ch3-33 frequency meter.

of particles and particle size, concentration, and velocity. The radiation sources here were two LG-75 He—Ne lasers operating in a multimode regime. The investigators studied the distribution and velocity of particles of burned magnesite of 150-600 μm in the jet from a 25-kW air plasmatron. The flow rate of the plasma-forming gas was 1-2 liters/sec. The optical elements of the system made it possible to form a 50-mm^3 study zone. The above-described methods made it possible to monitor the parameters of two-phase systems, especially in plasma-chemical production processes [30].

DETERMINATION OF PARTICLE VELOCITY IN A TWO-PHASE FLOW

Contact methods of measurement utilizing Pitot tubes and hot-wire anemometers are commonly used to measure local velocities in flows of liquid and gas. The high temperatures of plasma jets complicates the use of these methods even for determining the velocities in single-phase flows. Also, these methods introduce perturbations into the flows being studied.

Velocities in two-phase flows were previously measured mainly by the noncontact methods of photographing particle tracks [31-35] and determination of time of flight [35, 36]. The spatial resolution of these methods is low. The ISSO-1 velocity meter [33, 34] for luminous and illuminated objects developed by the Institute of Physics of the Belorussian Academy of Sciences is of interest for measuring the velocities of rectilinear motion of plasma jets, flames, and particles of powders. The meter permits measurement of the velocities of particles larger than 60 μm visually within the velocity range 20-830 m/sec and photographically within the range 10-1300 m/sec to within 10%. The time for a single visual measurement is 10 sec.

The Doppler laser velocity meter (DLVM) [37-40] is most promising for studying the velocity structure of flows. The meter operates on the principle of measurement of the Doppler

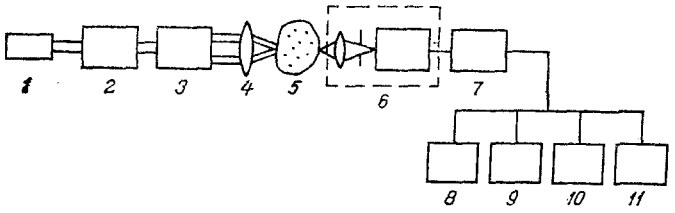

Fig. 7

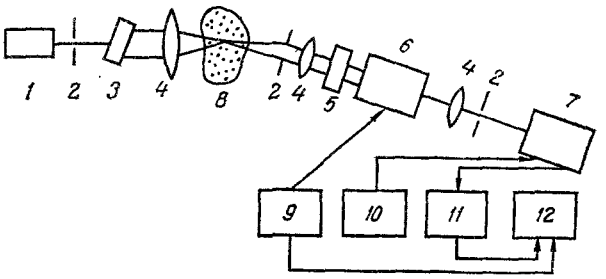

Fig. 8

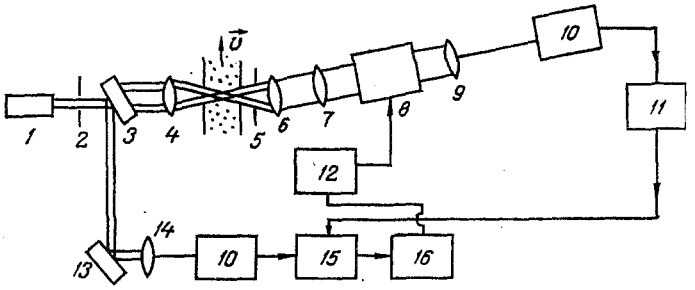

Fig. 9

Fig. 7. Optical DLVM system: 1) Lg-36 laser (He—Ne); 2) telescopic system; 3) optical-mechanical instrument; 4) lens; 5) flow being studied; 6) radiation detector; 7) amplifier; 8) S4-12 spectrum analyzer; 9) N-110 light-beam oscillograph; 10) S8-9A recording oscillograph; 11) Ch3-4A frequency meter.

Fig. 8. Optical DLVM system: 1) laser; 2) diaphragms; 3) dividing plate; 4) lenses; 5) interference filter; 6) scanning interferometer; 7) FÉU-79 photomultiplier; 8) flow; 9) scanning-synchronization block; 10) power-supply block; 11) U2-4 narrowband amplifier; 12) oscillograph.

Fig. 9. Optical DLVM system: 1) LG-159 laser; 2) modulator; 3) beam splitter; 4) lens; 5) diaphragm; 6, 7, 9, 14) lenses; 8) scanning interferometer; 10) photomultiplier; 11) U2-6 amplifier; 12) scanning block; 13) rotating mirror; 15) V9-2 synchronous detector; 16) S1-19B oscillograph or KSP-16 potentiometer.

shift of the frequency of laser radiation scattered on moving optical discontinuities, the shift being a linear function of the velocity of the discontinuity in the form $\Delta\nu_D = (\bar{k}_{sc} - \bar{k}_0)\bar{v}$.

The DLVM has the following advantages [38, 39]: noncontact principle of operation, wide range of measured velocities (10^{-6}-10^{6} m/sec), high spatial and time resolutions, respectively, up to 10^{-11} cm^3 and 10^{-7}-10^{-9} sec, high accuracy (0.2-3%), and the fact that the method is absolute. We can divide DLVMs into two groups with respect to the method used to measure the Doppler shift: the first group employs the method of photomixing, while the second group employs an optical spectral method. Here, the optimum limit of measured velocities for the first group of DLVMs is 500 m/sec, which is determined by the passband of the photodetector.

Mainly differential DLVM systems are used to study two-phase flows [39]. One such system is shown in Fig. 7. Along with particle velocity, the system permits determination of the dimensions of monodisperse particles in the 5- to 500-μm range (from measurement of the depth of modulation of the photoelectric current) and the bulk concentration (from measurement of the number of photoelectric current pulses).

It was shown in [41] that DLVM systems with spectrum scanning are more promising for studying the transient interaction of polydisperse particles and a gas in multiphase flows. Such systems make it possible to determine the particle-size and -velocity distribution functions. Fabry—Perot interferometers with plane mirrors and confocal spectrometers are used as scanning spectrometers, but the latter are more effective because of their greater resolution and transmission. A DLVM system with a conformal spectrometer is also preferable from

the point of view of sensitivity, time resolution, and simplicity when the scanning is done with a piezoelectric ceramic [6, 41]. Other scanning schemes — through changes in pressure and double optical-electronic conversion — are less suitable.

The study [6] presented a DLVM system with a conformal scanning interferometer on a piezoceramic (Fig. 8). The radiation source was a 5-mW LG-159 He—Ne laser operating in the single-frequency regime. The radiation scattered by the particles was recorded at an angle $\alpha = 31°44'$. The minimum value of the measured velocity was 10 m/sec, while the time resolution was as low as 10^{-4} sec.

A more sensitive unit [6] was developed to record particles smaller than 1 μm in diameter. This unit employs the method of synchronous detection to increase the signal-to-noise ratio. A diagram of the unit is shown in Fig. 9. The system permits recording a signal from scattered radiation when the signal-to-noise ratio ≥ 0.1, and it is particularly effective in experiments with a high background radiation (movement of particles in a flow of radiating gas, measurement of the velocity of burning particles, etc.).

There have been only a few studies involving the use of a DLVM to investigate heterophase plasma flows [30, 42-45] . The investigations [42, 45] were performed to determine the feasibility of using DLVMs to measure the velocity of microparticles in plasma jets. The plasma source was a 12- to 15-kW electric-arc plasmatron. The consumption of the plasma-forming gas, which was argon or an Ar—N_2 mixture, ranged within 2-40 liters/min. The researchers studied microparticles of the 0- to 50-μm fraction. They employed a differential DLVM system with generation of a Doppler signal by the photoheterodyne method. The system is depicted in Fig. 10. The radiation source was a 40-mW LG-36A He—Ne laser operated in the single-mode regime. The investigators also used an interference filter with a transmission maximum at the wavelength of the laser and a passband half-width $\Delta\lambda_{1/2} = 30$ Å. The measured particle velocities were distributed in the range 15-180 m/sec and were compared with the results of filming of the particle flow by a high-speed SKS-1M camera. The completed study [42, 43] showed that the DLVM has good time and spatial resolution and can be recommended for wide use in studies of heterophase plasma flows.

The works [44, 45] measured the velocities and temperatures of particles of Al_2O_3 of the 18- to 46-μm fraction when sprayed in a plasma jet to correlate spraying conditions with the quality of the coating. Particle velocity was measured with a differential DLVM. The radiation source was an argon laser. The measurement zone in the plasma jet was 1.3 mm in diameter. The measured particle velocities were within the range 150-300 m/sec.

The study [30] investigated the velocity of particles of burned magnesite of the 150- to 600-μm fraction in a jet of air plasma at gas flow rates of 1-2 liters/sec. The measured particle velocities were within the range 5-23 m/sec. A diagram of the DLVM is shown in Fig. 6. The DLVM developed for this study is recommended for use in monitoring production processes in plasma chemistry.

Apart from the above methods, particle velocity in two-phase flows can be measured by the method of impulse holography [18], which makes it possible to determine velocity from units of m/sec to hundreds of m/sec. There are no studies in the literature in which holography was used to record particle velocities in plasma jets, but several investigations have proven that holography can be used to study processes in the combustion of solid particles and in experiments with the explosion of conductors [18-20]. However, the complexity of using the holographic method and of analyzing the holograms, along with the difficulty of studying high-temperature two-phase flows, limits the application of this method for such objects.

DETERMINATION OF PARTICLE TEMPERATURE IN A TWO-PHASE FLOW

The methods available for measuring the temperature of suspended particles can be divided into contact and noncontact methods. Contact methods are limited by the highest temperatures that can be reliably measured by thermocouples (1000-1800°C), and they are difficult to use in measuring rapidly changing temperatures of moving particles.

The methods of radiation pyrometry have obvious advantages over contact methods in the following cases: in obtaining measurement in temperature ranges and media in which contact-type temperature transducers would not remain stable over a long period of time; when it is necessary to ensure quick response; when it is difficult or impossible to obtain contact between the subject and the thermal pickup (case of moving subjects); when contact cannot be made with the subject without distorting the temperature field. Also, radiation pyrometers have a practically infinite temperature range.

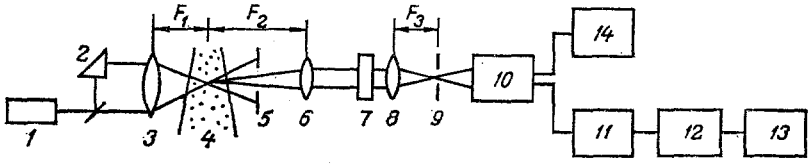

Fig. 10. Diagram of DLVM: 1) laser; 2) beam splitter; 3) lens with F_1 = 750 mm; 4) subject; 5) iris diaphragm; 6, 8) lenses with $F_{2,3}$ = 200 mm; 7) interference filter; 9) diaphragm with diameter 0.5 mm; 10) photomultiplier; 11) preamplifier; 12) U3-4 amplifier; 13) S4-8 or S4-25 spectrum analyzer; 14) power source of photomultiplier.

An important shortcoming of noncontact methods of temperature measurement is that radiation pyrometers allow measurement of the pseudotemperature of bodies. The difference between the pseudotemperature and the actual temperature is greater, the more the character of the radiation of the actual body differs from the character of blackbody radiation [46].

Features of temperature measurement with micropyrometers were examined in [47], while [48, 49] examined aspects of the pyrometry of subjects with a variable emissivity. The investigation [50] studied the feasibility of optical temperature measurements in two-phase media. It was shown that color methods are the most promising methods for determining particle temperatures and can increase measurement accuracy.

The following methods were used earlier [51] to measure rapidly changing temperatures (temperatures of plasmas, rotating parts, jets, etc.): 1) photographic — 1.5-2% temperature error in the range 500-3500°C, with a speed of several microseconds; 2) photoelectric — error up to 10% with recording on an oscillograph, speed hundreds of microseconds.

New pyrometers with a resolution in milliseconds have been developed [51]. The monochromatic pyrometer in [52] operates in the null regime with a speed up to 1200 measurements/sec. Work on high-speed temperature measurement is being done in the D. I. Mendeleev NPO VNIIM. Pyrometers have been developed to measure the temperature of impulsive radiators. The time resolution is several milliseconds, and the temperature measurement error is up to 0.3%. Operating with the same resolution is the "Spektropir-2" spectral-ratio pyrometer made by the "Lenteplopribor" Scientific-Industrial Association [53]. The range of temperatures measured by the pyrometer is 1300-1700°C, the error is ±1%, the sensitivity is 1-2°K, and the minimum size of subject is 2 mm. "Smotrich-3" partial-radiation pyrometers with a speed up to 0.01 sec are being readied for production at the Kamenets–Podol'sk Instrument Plant [54]. The temperature range is 1400-3500°C, the main error is no greater than 1-1.5%, and the sighting index is 1:200.

The Institute of High Temperatures of the Academy of Sciences of the USSR is conducting research on high-temperature measurements for metals and alloys [51]. Measurement time is several microseconds and the error is no greater than 1%.

Study [55] described a photoelectric pyrometer for measuring rapidly changing brightness temperatures in the range 1300-6000°K at six long waves. The brightness of the subject is compared with radiation from a standard source. The sighting index of the pyrometer is 1:400, the speed is 10^{-3} sec, and the main error is 1.2%.

Constancy of calibration in high-speed pyrometers is assured by the use of stable radiation from a reference source. For example, the pyrometer in [52] employs a shutter to successively expose the subject and a reference source, the radiation of which has n gradations. Temperature is determined from the ratio of the signal from the subject to the closest value of the signal from the calibrated source.

Study [56] described a method in which the signals from the subject and the reference source are not separated in time, and their ratio is determined in the interaction on a nonlinear element — a logarithmic amplifier. An operational amplifier was used as the latter in this case. The use of this method significantly increases the speed of pyrometers. Figure 11 shows a diagram of the pyrometer. Its speed is about 10^{-5} sec, the temperature range is 800-3200°C, and the temperature measurement is about 0.2%. The useful signal can be sent to a loop oscillograph and to a computer.

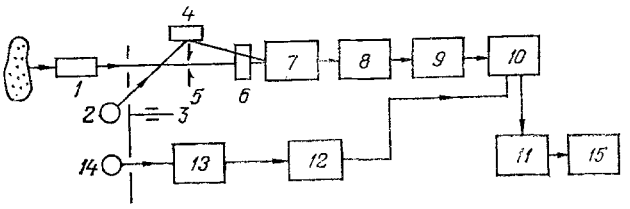

Fig. 11. Diagram of high-speed pyrometer: 1) optical element (sighting device and lense); 2) reference source; 3) shutter; 4) mirror; 5) field diaphragm; 6) filter; 7) radiation detector (FD-10G photodiode); 8) logarithmic amplifier; 9) high-frequency filter; 10) electronic switches; 11) detector; 12) auxiliary channel; 13) photodetector; 14) lamp; 15) recorder.

Investigations [57, 58] described a universal high-speed micropyrometer which permits measurement of rapidly varying (5000°K/sec) brightness and color temperatures, temperature pulsations, and brightness temperatures at two adjacent points in the temperature range 1000-3500°C with an error of ±1%. Figure 12 shows a diagram of the pyrometer. The pyrometer operates by the comparison method, which enhances measurement accuracy and calibration stability and alleviates the effect of electric fields. The pyrometer is universal because individual elements can be replaced (shutter, filters, diaphragms). The speed of the pyrometer ranges up to 2000 measurements/sec, the sighting index is 1:2000, and the minimum diameter of the subject is 0.1 mm.

Several studies have measured the temperature of burning or luminous particles [31, 32, 44, 45, 59, 60]. Investigation [31] determined the temperature of 50- to 200-μm particles of tungsten from the spectral distribution of radiant energy on the basis of the Wien displacement law. The method is complicated to use but is sufficiently accurate. The spectral radiant-energy distribution of particles in different sections of the plasma jet was recorded on a DFS-8 spectrograph. The signal was recorded with the aid of an FÉU-22 photomultiplier. The maximum error of the temperature determination was ±6% at a temperature of 3400°C.

Studies [32, 59] determined the temperature of tungsten particles photographically. The dimensions of the investigated particles were 50-100 μm. The error of the determination of the temperature 2200°C was ±20% and was connected with the indeterminateness of the spectral sensitivity of the photographic film, the emissivity of the tungsten, and inaccuracy in the photographic recording.

The investigations [44, 45] used a photoelectric pyrometer to measure particle temperature in a plasma jet. To measure the temperature of particles of 18-46 μm, the image of the 150-μm-diameter measurement volume was focused with lenses at the input of a photomultiplier. In [31, 32, 59], particle velocity was found to be in the range 25-50 m/sec. In [44, 45], particle velocity reached 150-300 m/sec.

The work [60] described a color photopyrometer used to measure the temperature of stationary burning particles of coal 150-800 μm in size. The use of three filters made it possible to cover the temperature range 900-3000°C. The radiation detector was an FÉU-22 photomultiplier. The pyrometer calibration error was 1-2%, while the speed ranged up to 200 measurements/sec.

The Institute of Physics of the Academy of Sciences of the Belorussian SSR has developed a two-channel SM-2 spectrometer and an automatic ASK-3 spectrometric complex to analyze plasmas, electric

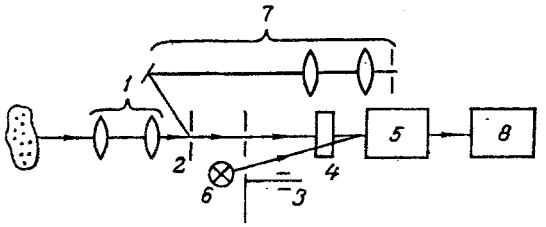

Fig. 12. Diagram of micropyrometer: 1) dual-lens system; 2) field diaphragm; 3) shutter (3000 rpm); 4) KS-15 filter; 5) FÉU-51 photomultiplier; 6) standard lamp; 7) sighting system; 8) oscillograph.

arcs, and other spatially uniform and nonuniform objects [61, 62]. The ASK-3 complex has the following characteristics: working spectral range 200-1200 nm, resolution up to 25,000, dynamic range of radiation-intensity recording 10^5, spatial scanning speed 200 intervals/sec, spectral scanning speed 1000 intervals/sec.

The temperature of luminous moving particles can also be measured by the methods of photographic pyrometry [63-66]. Photographic pyrometers make it possible to determine brightness and color temperatures, have a high sensitivity and resolution, are characterized by high accuracy in measuring differences and gradients of temperature, and can record nonstationary temperature fields of moving or stationary objects. The most serious shortcoming is the time required to analyze the photographic film. This problem has been alleviated considerably by development and photometric techniques. Any photographic or motion-picture camera equipped with a filter (such as the SKS-1, SFR-1, etc.) can serve as a color pyrometer.

It was concluded in [62] that the limiting standard deviation of brightness temperature measurement in the range 1000-3000°C is ±0.5% when photographic pyrometry is used. The error for the color temperature is ±2%. The maximum error of the measurement of a temperature difference of, say, 40°C at 1700°C is ±2%.

Particle temperature can also be determined by the method of the intensity of the saturated center of a spectral line [67, 68], the method of radiation and absorption in the presence of measured or calculated scattering coefficients and attenuation factors [69, 70], and the method of holographic interferometry [18] if the local concentration of particles in the two-phase system is known.

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