Prospects of Application of FiberOptic Sensors for Studying the Combustion Processes in Two-Phase Flows with High Concentration of Disperse Phase [Review]

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Abstract. The review is focused on the prospects for using the fiber-optic sensors (FOS) to study the combustion processes and measure the actual parameters (particle velocity and concentration, temperature and its distribution in the object, pressure, deformation, acceleration, displacement, etc.) in two-phase flows and sites of difficult access at high temperatures (800ºC and higher).

1. Introduction

As it is known, combustion is the main source of energy in the world; fossil fuel combustion gives up to 90% of all energy (2010) produced on Earth. However, with the growth of energy consumption, it is necessary to solve global problems associated with depletion of non-renewable energy resources, environmental pollution and global warming. Combustion processes are widespread in modern technologies, it is necessary to study the structural characteristics of the flame in internal combustion chambers, flameless combustion in circulating fluidized bed (Thermal Power Plants and State District Power Plants), filtration catalytic combustion, etc. They include such stages as formation of a combustible mixture, ignition, flame propagation and radiation, chemical transformations and heat release, multiphase flows, turbulent mass transfer, etc.

To study the totality of complex combustion processes, optical methods are the most informative, they include: visualization (including high-speed video shooting), miniature vision systems (including endoscopes), LDA, PIV, PTV, LIF, fiber-optic sensors (FOS) and others. [1-11]. It is noted in [1, 2] that the need for such sensors is growing rapidly due to the rapid development of automated control and management systems, introduction of new technological processes, and transition to flexible automated production. In addition to high metrological characteristics, the sensors should have high reliability, durability, stability, small dimensions, mass and energy consumption, compatibility with microelectronic devices for processing information at low labor intensity and low cost. The fiber-optic sensors met these requirements to the maximum degree, and this review is focused on them. The use of FOS at high temperatures (800ºC and higher) is accentuated here.

In sensors, an optical fiber can be used both as a transmission line and the most sensitive element, which converts a certain physical effect into a change in the properties of transmitted, reflected or scattered radiation. The main features of the measurement schemes with the help of FOS and their application are given in [1-3]. They summarized the experience of development and application of
fiber-optic converters of various physical quantities, considered methods for presenting information, types of FOS, optical fibers, light-emitting and light-receiving devices, and elements of optical schemes. In [4], an overview of optical, fiber and integrated optical sensors of physical effects is given. The sensors are classified according to the principle of operation; sensors of amplitude, interference and polarization types are described. The descriptions of the sensor designs (or their sensitive elements), mechanical parameters (displacement, force, acceleration), acoustic vibrations and pressure, electric and magnetic fields, current, temperature, angular velocity, etc., as well as some of their main characteristics are presented there. Laser-optical methods for diagnosing the combustion processes are presented in [5]. The general characteristics of laser-optical methods for diagnosing the combustion processes (PIV, LIF, PTV, LDA, CARS, etc. based on traditional optics) and their comparison with the contact methods are presented. Particular attention is paid to the methods for determining the velocities of gas and particles, droplet sizes, concentration of combustion products, flame temperature, etc. Fiber-optic sensors have the following advantages over the traditional analogs [2]: immunity to electromagnetic fields and disturbances; resistance to radiation; resistance to complex climatic conditions and aggressive chemical environments; fire and explosion safety; they are not affected by corrosion; there is no need for electrical power, earthing and galvanic isolation; the sensor can be at a great distance (tens of kilometers) from the reader; short response time of the sensor, low thermal inertia; possibility of sequentially connection of many sensors into a single chain; higher resolution and less error in comparison with classic solutions; compactness; service life of 20 years, etc.

2. Fiber-optic sensors for measuring particle velocity and concentration. Heat-resistant telescope for visual studies of combustion processes

The fiber-optic sensors for measuring the velocity and concentration of particles in highly concentrated two-phase flows were developed at Kutateladze Institute of Thermophysics SB RAS. To visualize various thermal-physical processes and perform measurements in two-phase flows with high concentration of a disperse phase, an original rigid visual tube (endoscope) was developed. Its distinctive features are as follows: simplicity of design with acceptable image quality, making their production significantly cheaper (almost by an order); possibility of making tube 1 in the form of a removable disposable head; high reliability, surpassing the world analogues at relatively low cost price. At pulse illumination of a two-phase medium, it is possible to measure the velocity and concentration of a disperse phase using PIV, PTV, LDA, etc. A schematic diagram of the endoscope with a spherical lens, corresponding to United States Patent (No.: US 7,018,330 B2, Date of Patent: Mar., 28, 2006) is shown in Fig. 1 [12].

![Figure 1](image-url) A schematic diagram of the endoscope with a spherical lens.

The possibility of using a tube for studying the combustion processes in two-phase flows at high concentration of the disperse phase at medium temperatures of up to 800°C and higher (boiling and circulating fluidized bed, filtration combustion, etc.) is determined by the following factors: four optical elements can be made of quartz glass with the maximal operating temperature of above 800°C; the fiber light guides with a metal sheath and maximal operating temperature of above 800°C can be
used to illuminate the object; operability of the optical scheme is not disturbed when the tube is deformed by up to 0.5-1.0 mm; possibility of cooling the working part of the tube by an external source.

The one-, two- and three-fiber optic sensors are considered in [13]. These sensors are used in the differential and inverse-differential schemes of the laser Doppler anemometer (LDVA-3) and LDVA-1 with a reference beam, developed at IT SB RAS for measuring the velocity and concentration in two-phase flows with high concentration of disperse phase. In these schemes, the optic fibers play the role of the blocks of LDA shaping and receiving optics. Using the fiber light guides with a metal sheath, it becomes possible to measure the velocities and concentrations of particles on the in-site objects (in combustion processes), and perform measurements inside high-temperature chemical reactors, etc.

Let us consider a modified two-fiber sensor for measuring the thickness of a liquid film in hard-to-reach places and in-site objects as well as movement and distance to the object as an example. A flowchart for measuring the thickness of a liquid film by a modified two-fiber sensor with a metal sheath, which expands its application to the objects with high (up to 800°C and higher) temperatures, is shown in Fig. 2. The beam of He-Ne laser 1 is introduced into probing light guide 3 by means of gradient lens 2. Receiving light guide 5 is located adjacent to light guide 3; 1.6-mm thick quartz plate 4 is glued to their ends. The tip of the two-fiber sensor is fixed in a sleeve, which is mounted flush with the streamlined surface. In the presence of a liquid film, the reflected light is partially introduced into light guide 5 and sent to photodetector 6. Then, the electronic signal is processed on computer 7. In the modified sensor, there is a unique relationship between the output voltage and distance to the reflecting surface. Using this modified two-fiber sensor, the liquid film thickness can be measured, as well as velocity and concentration of a disperse phase in highly concentrated two-phase flows. The velocity of the disperse phase can be measured by the Doppler frequency shift in the light scattered by the particles (by the analogy with LDVA-1), and disperse phase concentration can be measured by the analogy with the reflective type sensors.

![Figure 2](image_url)

**Figure 2** Flowcharts for measuring the thickness of a liquid film by the modified two-fiber sensor.

Such a sensor has a number of advantages: high speed ($10^{-4}$-$10^{-5}$ s), small area of film surface sounding (~ 0.12 mm²), high measurement accuracy (1.5-2% for smooth films, 10% for wave films) and long communication line between the object and sensor (more than 100 m). Application of a modified two-fiber sensor for investigating the mechanism of flow spreading in a counterflow of air in a distillation column with a corrugated packing is demonstrated in [14], and its use for measuring the liquid film thickness on an object with a local heater is shown in [15]. The use of a three-fiber LDA (LDVA-3) of the differential type for measuring the velocity and concentration of particles in a large-scale apparatus with a circulating fluidized bed is shown in [16].
3. Development of FOSs and fiber light guides with a metal sheath at Fiber Optics Research Center and Institute of Radio-Engineering and Electronics of the Russian Academy of Sciences

In Russia, the Fiber Optics Research Center of the Russian Academy of Sciences (FORC RAS, guided by Academician E.M. Dianov) was created in 1993 on the basis of the Fiber Optics Department of the Prokhorov General Physics Institute of RAS [18-22]. FORC RAS (http://www.fibopt.ru) conducts fundamental and applied research on a wide range of problems of modern fiber optics, including the development of various FOSs (interferometric ones and sensors operating on the fiber gratings of refractive index), temperature, pressure, displacement, deformation, vibration, mechanical stress, etc.

Fiber light guides with a metal coating (Al, Cu) for the use under severe environmental conditions were developed. They have the following advantages: allow higher operating temperatures (up to 800°C), increased tightness, mechanical strength and fatigue resistance, the transmission coefficient covers the spectral range from 200 to 2400 nanometers, and remains stable in the environment of chemical corrosion (temperatures from -196°C to +750°C and humidity of up to 100%). LLC “FORC – Photonics” (http://www.forc-photonics.ru) is engaged in the development, production and implementation of FOSs.

Fiber-optic technologies, devices, sensors and systems are being developed at the Institute of Radio-Engineering and Electronics of the Russian Academy of Sciences [21], and fiber light guides with a metal sheath are being developed at the Institute of Radio-Engineering and Electronics RAS (Fryazino Branch), Fryazino, Moscow Region, Russia) [22].

4. Industrial FOSs and fiber light guides with a metal sheath of JSC “Perm scientific-industrial instrument making company”, LLC “Inversion-Sensor”, and LLC “Monsol Rus”

The “Inversion-Sensor” company [23] has been developing the fiber-optic sensors and introducing monitoring systems since 2004. The company began its development on the basis of the fiber optics center at the Institute of Automation and Electrometry SB RAS and Technopark of Novosibirsk Academgorodok. Since 2013, LLC “Inversion-Sensor” and JSC “Perm Scientific-Industrial Instrument Making Company” (Perm) have joined forces in the development and production of the point and distributed fiber-optic sensors. Serial production is located in Perm on the industrial site of the industry cluster “Photonics”. The products include the following sensors: temperature, pressure, deformation, displacement, tilt angle, vibration, signal analyzers, multiplexers, fiber Bragg gratings (FBG), and distributed temperature sensors. In [23] it was shown that sensors based on fiber Bragg gratings (FBG) and distributed sensors based on Raman effect are considered the most promising for measuring the physical parameters.

When laser radiation passes through the fiber, a part of it is reflected from the grating at a certain wavelength (Fig. 3). This peak of reflected radiation is recorded by the measuring equipment. As a result of the influence of many physical parameters, the interval between the Bragg grating nodes changes, as well as the refractive index of the fiber. The wavelength of radiation reflected from the grating changes correspondingly. The exact characteristics of changes can be determined by changing the wavelength. In modern signal analyzers, it reaches 1 pm (~0.1°C, ~10^-6 rel. units).

Figure 3 Flowchart of FBG-based FOS for measuring temperature and deformation [24].
The distributed temperature sensor (with the length of up to 8 km) based on Raman scattering includes the following main elements: pulsed laser and an optic fiber connected to the source, which is a sensitive element [23]. When an incident photon and matter molecule exchange the energy, a transition from the ground vibrational state to the excited state occurs, at which the scattered photon is displaced in frequency to the red region of the spectrum and, thus, the Stokes component is generated. But an inverse process is also possible when a structural molecule loses energy and re-scattered photon with a higher energy generates an anti-Stokes line in the blue region of spectrum relative to the excitation line (Fig. 4). Population of the excited level depends directly on the substance temperature; the intensity of anti-Stokes component will also demonstrate the temperature dependence. Registering the time dynamics of anti-Stokes component intensity, when probing by pulsed radiation, the temperature can be measured by this sensor along the entire fiber.

![Spectrum of diffused impulse.](image)

Figure 4 Spectrum of diffused impulse.

The system is characterized by a wide range of temperature measurements (from -55 to +300°C), high accuracy (up to ± 0.5°C), high spatial resolution (up to 0.5 m). The spheres of application of distributed thermometry systems include: temperature measurement and fire notification on the extended objects (mine workings, tunnels, etc.); thermomonitoring of oil and gas wells, cable lines, pipelines, etc.; control of filtration processes at hydraulic structures, etc.

The main profile of LLC “Monsol Rus” (Zelenograd, https://monsol.ru) is creation (and sale) of automated monitoring systems (including fiber-optical sensors of deformation, pressure, temperature, vibration, etc.): buildings and structures, transport infrastructure, hydropower engineering, nuclear and aerospace industry, etc. In addition, in July 2018, the company became the official distributor and integrator of the company Fiber Optic Security Systems LLC. A new fiber-optic perimeter security system and vibro monitoring of CBM is designed to protect the borders of airports, military and other strategic facilities, oil and gas pipelines, large industrial enterprises and factories.

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