Modelling the optical part of a tomographic system for measuring the gas flow local temperatures

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Abstract. This paper describes a technique for modelling the optical part of a tomographic system for measuring local temperatures of a gas flow. The system is based on the use of a spectral ratio pyrometer. The parameters of the optical part of the tomographic system with a lens part of two configurations are modeled: a single lens and a single lens paired with a microscope objective lens. Diagrams of scattering spots, illumination distributions in the cross section of the beam, and average values of the total radiation power in the focal plane of the optical system are obtained. Recommendations are given for the elimination of parasitic illumination in a pyrometer, as well as for further improvement of the tomographic system lens.

1. Introduction
Measuring the temperatures of aircraft engine elements and the temperatures of the gas flow is an important task in fine-tuning the development and operation of industrial units [1]. Such measurements provide information on the state of engine components and its important characteristic such as thrust. This problem can be solved by contact measurement methods using thermocouple probes. However, the use of contact measurement methods leads to the introduction of perturbations into the medium under study. In addition, using thermocouples is a difficult task at sufficiently high temperatures (above 2000 K) due to limitations in their operating range. For solving this problem methods of optical pyrometry are widely used. They have two advantages: they are contactless and fast [2-3].

The two simplest types of optical methods for measuring the gas flow temperature are measurement with the help of emission and absorption. The second type [4] is more complicated due to the necessity of using additional equipment, which is not always possible. One of the emission methods is the method of measuring the gas flow temperature based on the ratio of the spectral lines of the two components of its radiation. The ratio of radiation intensities does not depend on the concentration of the particles in the gas, which makes it possible to determine the temperature. This method is implemented in the form of a compact device called a spectral ratio pyrometer [5], which allows measuring the gas temperature in the range of 1000-2500 K.

An important task in fine-tuning the developed and operating industrially produced elements of aircraft engines is their testing with visualization of the results obtained in the form of a temperature field. The transition from local measurements to field measurements allows specialists to obtain a qualitatively new picture of the processes under study, which can be used to improve the design of aircraft engines.
A pyrometer operates by measuring the integral radiation intensity along the line of sight. Therefore, to measure local flame temperatures with its help, the tomographic approach was chosen [6]. Tomography is a set of methods, allowing with multiple measurements of the one dimension to reconstruct the distribution of the physical quantity in the dimension greater by one. The mathematical basis of tomographic methods is the Radon transform [7].

2. Modelling technique

The tomographic approach used to construct a system for measuring local flame temperatures requires a many optoelectronic channels, including expensive lenses and photodetectors. A distinctive feature of the system considered in this article is the presence of scanning mirrors [6], which makes it possible to implement five channels, each of which transmits radiation from the local region of the gas flow to the main optical system.

The modeling was performed for three wavelengths of the lines of the water vapor spectrum: 0.98 μm, 1.38 μm, and 1.48 μm. The layout of the mirrors is shown in figure 1. The mirrors are located on a circle with a diameter of 700 mm. Thus, four measuring channels and one multiplexing channel are realized. The subsequent optical system concentrates the radiation on the receiving aperture of the pyrometer - the end of the fiber bundle 3 mm in diameter. To separate the radiation into spectral channels, the fibers of the bundle are divided into three beams. Radiation from each beam enters the photodiode, passing through a narrow-band interference filter, which provides transmission at one of the wavelengths under study. The flame temperature is determined by the ratio of the radiation intensities measured in different spectral channels.

As mentioned above, to separate the radiation over the spectral channels, the fibers of the bundle are distributed approximately equally into three parts, while it is not clear how uniformly this separation occurred. It can be expected that more fibers from the more illuminated part of the receiving aperture will fall into a certain beam. As follows, the fraction of the radiation that has entered in one spectral channel, is not equal to another. Thus, the purpose of modeling the optical scheme of the tomographic system based on a spectral ratio pyrometer is to analyse the illumination distribution over the plane of the input end of the fiber bundle.

Two configurations of the tomographic system optics were modelled. In the first a single lens LBF254-050 with a focal length of 50 mm from ThorLabs was used. The lens is designed for minimum spherical aberration. An uncoated lens was chosen, since the range of coatings offered by the manufacturer in the IR region (0.65÷1.05 μm or 1.05÷1.70 μm) does not provide transmission in the entire range from 0.98 μm to 1.48 μm. In the second configuration with the single lens an additional 8×0.2 microscope objective lens from the OSK-2 bench manufactured by the NOVOSIBIRSK
INSTRUMENT-MAKING PLANT, JSC was used. The objective lens helps to increase the diameter of the light spot in the plane of the fiber bundle end. In both configurations we used flat round mirrors PF20-03-M01 with a gold reflecting coating 50.8 mm in diameter also from ThorLabs.

Switching between pyrometer mirrors is simulated in both sequential and non-sequential modes using multi-configuration. The analysis of radiation transmission along the entire path of the tomographic system, taking into account the properties of the radiation source and reflection losses, was performed in a non-sequential mode, which is also more suitable for creating non-imaging systems and spatial systems with several channels [8].

The use of the sequential component mode does not allow evaluating the illumination distribution at the end of the fiber bundle considering the properties of the source, reflection losses, parasitic glare, etc. Therefore, the modeling was performed in a non-sequential mode. Here, the position of the elements is set in an arbitrary order, while all the elements of the optical scheme are displayed and take part in the formation of the image at the same time, unless otherwise specified by the user. Figure 2 shows a diagram with a ray path for the fifth measuring channel. Despite the fact that the beams have several reflections, only a small part of the displayed rays reaches the receiving area: 1 out of 20,000. To calculate the illumination, a larger number of rays are traced at the detector, in this case 30,000,000.

![Figure 2. Diagram with a ray path for the fifth measuring channel.](image)

For an emitting object, we chose a volumetric elliptical source of the blackbody type, emitting in the range from 0.98 µm to 1.48 µm and the temperature of 1750 K which is the middle of the temperature range measured by the pyrometer. The selected type of object allows to specify a sphere-shaped source if the dimensions of the ellipsoid semi-axes are the same along three axes. In this case, a sphere with a radius of 50 mm was modeled, which corresponds to a diameter of the measured field of 100 mm [5]. A rectangular detector measures 1.5 mm × 1.5 mm (half-width in X, Y coordinates). To simulate a circular receiving platform, a diaphragm with a diameter of 3 mm is placed close to the detector.

3. Modelling results
In the first modelled configuration a single lens concentrates radiation in a spot with a diameter of about 1 mm. From the diagram shown in figure 3 can it be seen that radiation at a wavelength of 0.98 µm illuminates a larger area than radiation of other wavelengths. The spot diameter for 1.38 µm is 0.85 mm, for 1.48 µm 0.78 mm. This radiation distribution is due to chromatic aberration, which cannot be eliminated with a single lens. When the detector plane is displaced, the ratio of the spot sizes for different wavelengths will change, but it is impossible to find a plane in which the radiation of all three wavelengths would illuminate the receiving area equally. Thus, it is impossible to predict in what proportion the separation of radiation of different wavelengths along the fibers will occur, and hence how the radiation will be distributed along the spectral channels.
When switching channels, the position of the focal plane is shifted within 1.5 mm and can be compensated for both by moving the lens and by moving the detector plane. In the first case, the sizes of the focal spots will also vary insignificantly.

In the second model configuration the scheme was supplemented with a microscope objective lens to ensure complete illumination of the input aperture of the fiber bundle. The lens builds an intermediate image, which is then enlarged using the 8×0.2 microscope objective lens. When the focal planes of the lens and the objective are aligned, the diameter of the parallel beam emerging from the objective is three times the diameter of the receiving area, which leads to a loss of about 90% of the energy, so the lens was installed a little further to ensure that the end of the fiber bundle is illuminated with a converging beam. The distance from the focal plane of the lens to the first refractive surface of the objective is selected in such a way as to concentrate the greatest part of the energy on an area with a diameter of 3 mm, corresponding in size to the end of the fiber bundle.

Figure 4 shows diagrams obtained for the third measuring channel, schematically showing the distribution of radiation of different wavelengths in the plane of the receiving area, both for polychromatic radiation and for each wavelength separately. As can be seen, the use of the microscope objective lens makes it possible to provide full illumination of the fiber bundle aperture to some extent. However, the illumination will still not be uniform due to the significant chromatism of the system. Most of the radiation at a wavelength of 0.98 μm is collected in a spot with a diameter of about 1 mm, the rest is scattered into a halo with a diameter of 4.8 mm, radiation at wavelengths of 1.38 μm and 1.48 μm is collected in spots with diameters 2.3 mm and 2.56 mm respectively. An additional inconvenience in operation is the need to change the position of the microscope objective lens and the input end of the fiber bundle when switching the measuring channels.

In non-sequential mode, the distribution of illumination along the plane of the detector, the value of the threshold illumination, as well as the total power of radiation that hit the receiving area are displayed in the Detector Viewer window. Figure 5 shows this window for the first measurement channel without the microscope objective lens, the diameter of the receiving platform is 3 mm. The detector is located in the focal plane of the lens.

When re-tracing rays, the values of illumination and radiation flux change are found to be within acceptable limits. The amount of peak illumination depends on the Smoothing parameter. Since channels 2 and 5 are symmetrical, you can expect identical power and luminance values for them. However, a comparison of them showed that for the case when all the mirrors are in the nominal position, the total radiation power at the receiving area for channel 2 is greater than for channel 5. During the study it was
assumed that radiation from other mirrors falls on multiplexing mirror 1. By sequentially turning off the mirrors, it was found that when channel 2 was in operation, radiation from mirror 5, which was parasitic for channel 2, entered the pyrometer lens. To exclude parasitic radiation mirror 5 was rotated by 45° in subsequent modelling.

Figure 4. Scatter plots in the plane of the detector for all wavelengths with microscope objective lens, blue – \( \lambda = 0.98 \, \text{\textmu m} \), green – \( \lambda = 1.38 \, \text{\textmu m} \), red – \( \lambda = 1.48 \, \text{\textmu m} \).

Despite the fact that the total radiation power at the receiving site is not high, the subsequent amplification in the electronic path of the pyrometer allows registering the signal. A bigger problem is the uneven illumination end of the fiber bundle. The requirement to uniformly illuminate the receiving area with a diameter of 3 mm cannot be fulfilled using a single lens; therefore, the scheme was supplemented with the microscope objective lens. However, an analysis of the illumination distribution in an non-sequential mode showed that in this case a very small fraction of radiation falls on the receiving area: about 1 \( \mu \text{W} \) for a radiation source power of 1 W and 30,000,000 traced rays, a further increase in the number of traced rays does not lead to an increase in the calculated radiation power hits the detector.

4. Conclusions

To analyse the distribution of illumination over the receiving area of a pyrometer, an optical scheme of the tomographic system was modelled in sequential and non-sequential modes using the multi-configuration mode to implement switching between the measuring channels of the pyrometer. Setting the optical scheme in a non-sequential mode makes it possible to take into account the action of all five
mirrors at once, and not in the order of switching on the configuration, which corresponds to the actual state.

Two types of configuration are considered: with a single lens as an objective and with the additional use of the scope objective. Analysis of the ray path in sequential components mode showed that a spot with a diameter of 1 mm is formed in the focal plane of a single lens. For the microscope objective lens, it is possible to obtain such a focal spot that the bulk of the energy is concentrated within a circle with a diameter of 3 mm, however, it is not possible to achieve equal spots for radiation of different wavelengths.

![Figure 5.](image)

Analysis of the distribution of illumination in non-sequential components mode showed that the use of the microscope objective lens leads to a decrease in the share of energy falling on the end of the fiber bundle. It was also found that during the operation of the second measuring channel, a flare appears due to the symmetrical arrangement of mirrors 2 and 5. To eliminate parasitic illumination, the mirrors that do not participate in the formation of the current measuring channel must be oriented in such a way that the light from them does not fall on other mirrors and pyrometer lens.

The need to uniformly illuminate the end of a fiber bundle with a diameter of 3 mm with radiation of three wavelengths leads to a complication of the pyrometer lens, which in turn significantly reduces the energy characteristics of the system. Further improvement of the optical system of the tomographic system can be implemented in two ways. The first option is designing an optical system that contains two parts - an objective and an eyepiece, with variable magnification (necessary when changing measuring channels) and with apochromatic correction and antireflection in the range of working wavelengths. The second is changing the spectral beam splitting scheme, meaning replacing the fiber bundle with other beam-splitting elements (prism, set of plates, etc.), which will make it possible to implement a much simpler scheme of the pyrometer lens and thereby reduce energy losses in the optical path of the tomographic system.

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