# SOME ASPECTS OF PYROMETRY OF "WHITE" OBJECTS

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## Introduction

Model surface temperature up to 2000-2500°C should be measured in thermal wind tunnels. The basic method of surface temperature distribution measurement is the brightness pyrometry. The brightness pyrometers measure absolute value of power emitted by the heated surface at a chosen wavelength. There are some spectroscopic components in the design of such pyrometers, the simplest of which is a narrowband optical filter. Brightness pyrometers measure the brightness temperature, and it is necessary to know the emissivity of the object material to recalculate brightness temperature to the real surface temperature.

In technology new materials are used as structural materials exposed to high temperatures. Thermo-physical properties of these materials, including their emissivity, are to be studied. Often these materials are white and have emissivity in the visible wavelength range less than 0.1. The minimal change of such low emissivity values or minimal error of this value leads to a significant error of temperature determination according to the formula:

$$\frac{\Delta T}{T} = -\frac{\lambda k T}{hc} \cdot \frac{\Delta \varepsilon}{\varepsilon}, \tag{1}$$

obtained by differentiating the Plank`s law. Thus, it is necessary to measure the emissivity of the investigated white materials quite precisely while performing tests in wind tunnels.

The possibility of emissivity determination by means of brightness and spectral pyrometry is investigated in this paper.

## Physical principles of pyrometry

Pyrometry includes the temperature measurement methods based on registration of thermal radiation of the investigated objects. The main application requirement of pyrometry methods is that the radiation of the investigated objects is thermal, i.e. that the radiation is in the equilibrium with substance and, therefore, the Kirchhoff's law is valid. According to the Kirchhoff's law the ratio of the radiating capacity $u(\lambda,T)$ of the body (the power emitted by the unit of surface area per time unit) to its absorptivity $\alpha(\lambda,T)$ (the ratio of absorbed power to the power of the incident flux) does not depend on the nature of the radiating body and is equal to the radiating capacity of blackbody $u_0(\lambda,T)$:

$$\frac{u(\lambda,T)}{\alpha(\lambda,T)} = \frac{u_0(\lambda,T)}{1}. \tag{2}$$

Blackbody is the body absorbing all the incident radiation at any wavelength, i.e. that the absorption coefficient of blackbody is equal to 1. There are no real blackbodies in nature. The difference between the radiance of investigated body and of blackbody is characterized by the emissivity $\varepsilon(T,\lambda)$, which is equal to absorptivity $\alpha(T,\lambda)$. There are substances with emissivities which do not depend on emission wavelength $\lambda$ in some wavelength range. Such bodies are called gray bodies.

The dependence of the radiating capacity of blackbody on wavelength and temperature is determined by the Plank's law, which is the foundation of pyrometry:

$$u_0(\lambda,T)=\frac{2\pi hc^2}{\lambda^5}\cdot\frac{1}{\exp(hc/k\lambda T)-1}=\frac{c_1}{\lambda^5}\cdot\frac{1}{\exp(c_2/\lambda T)-1}, \quad (3)$$

where $c_1$=3,7515*10$^{-16}$ W*m$^2$ and $c_2$ = 1.43879*10$^{-2}$ m*K. For low temperatures $T < 2500$ K the unit in the Plank's law can be omitted (Wien's approximation).

Pyrometry methods can be divided into radiation, brightness and color (spectral) methods depending on the measured radiation parameters of heated surface.

Radiation pyrometers measure the absolute value of the total radiation power of heated surface. Radiation pyrometers require detectors, acquiring the radiation of entire spectral range. The accuracy of radiation pyrometers is quite low since the real bodies can be considered as gray only in some restricted spectral range. External illumination can also affect the accuracy of such measurements significantly.

Brightness pyrometers measure the absolute value of radiation intensity of heated surface at a certain wavelength. The brightness temperature $T_b$ of the body with a spectral radiating capacity $u$ is the temperature of blackbody that has the same value of spectral brightness at the wavelength of measurements. The customers usually need to know the real temperature of the investigated surface that can be obtained if the emissivity of the investigated body is known.

Calibration curve of the brightness pyrometer is obtained by taking the logarithm of the Planck's law (3) in the Wien approximation as:

$$\ln(I)=\ln\left(\frac{c_1}{\lambda^5}\right)+\ln(\varepsilon(\lambda,T))+\ln(F)-\frac{c_2}{\lambda T}=A-\frac{c_2}{\lambda T}, \quad (4)$$

where $I$ is the signal acquired by pyrometer and $F$ is the light collection function of brightness pyrometer, including also the transmission of all optical elements of the measurement system, spectral sensitivity of the instrument and conversion parameters of the measurement system. Calibration characteristic of brightness pyrometer is linear in the coordinates ln($I$) and 1/$T$ with 1/$\lambda$ slope, i.e. the slope of the characteristic depends on the wavelength of acquisition only. Brightness pyrometer should be calibrated in conditions of the experimental facility to find its collection function, thus obtaining the calibration constant $A$, and then the stability of collection function should only be provided during the experiment.

Color pyrometers measure the brightness of the heated surface at two or more wavelengths and color body temperature $T_c$ is determined by the ratio of brightness according to the Planck's law (3). It should be noted that color temperatures are the same for the black and gray bodies. The main advantage of color pyrometers is that the temperature measurement does not require the absolute calibration of the pyrometer by radiation intensity and it is very attractive for some tasks.

Works on color temperature measurements were made intensively in TsAGI 25-30 years ago [1]. It was found that the temperature determined from the intensities at two wavelengths is extremely sensitive to external illumination. Additionally, the hypothesis of body "grayness" at selected wavelengths is always questionable.

Writing the Planck's law (in Wien's approximation) as:

$$\ln(I\cdot\lambda^5)=\ln(\varepsilon(\lambda,T)\cdot c_1)-\frac{c_2}{\lambda\cdot T}, \quad (5)$$

the radiation spectrum of a gray body becomes linear in the coordinates (ln($I\,\lambda^5$), 1/$\lambda$) with the $c_2$/$T$ slope. The slope does not depend on emissivity for gray bodies and thus the body temperature can be determined without the knowledge of the emissivity value. Thus, it is possible to choose a linear part of body thermal radiation spectrum in Wiens coordinates (ln($I\cdot\lambda^5$), 1/$\lambda$) that is free from external illumination, and to find "spectral" temperature of body thermal radiation $T_s$ by the slope of the curve. Since the whole spectrum is under consideration but not a set of two or three intensities at fixed wavelengths, it is possible to choose the correct spectral range and to evaluate the body "grayness" hypothesis satisfaction. It should be noted that the spectral temperature is determined

correctly without $\varepsilon$ value for gray bodies, but an error of the spectral temperature can be unpredictable if the body is not gray.

If absolute calibration of the spectrometer with blackbody is performed, the brightness temperature $T_b$ can be obtained for each wavelength in addition to the spectral temperature. Then emissivity of the body can be determined by the ratio of the emissive capacity of the blackbody at temperatures $T_b$ and $T_s$:

$$\varepsilon(\lambda, T_s) = u_0(\lambda, T_b) / u_0(\lambda, T_s). \quad (6)$$

**Measurement of the spectral and brightness temperatures by spectrometer**

The appearance of spectrometers with registration of the spectrum by CCD array provides the progress in the measurement of color, or rather, the spectral temperature [2, 3]. The usage of CCD arrays in such spectrometers allows recording the entire spectrum simultaneously, that is necessary for investigation of the rapid processes.

Compact spectrometer OceanOptics USB2000+ with a CCD array was used in the presented work to register the emission spectrum of the models. Main technical characteristics of spectrometer are:

- CCD array: Sony ILX511B;
- Spectral range: 339-1025 nm;
- Number of pixels: 2048;
- Pixel size: 14 μm x 200 μm;
- ADC: 16 bit;
- Integration time: from 1 μs to 65 s.

The radiation of investigated body is collected from the selected point of the surface by collimator and is transmitted to the spectrometer by optical fiber. Spectrometer control and data acquisition is performed by computer via USB port using specific software. The program provides full control of operating modes of the spectrometer and record acquired data in file.

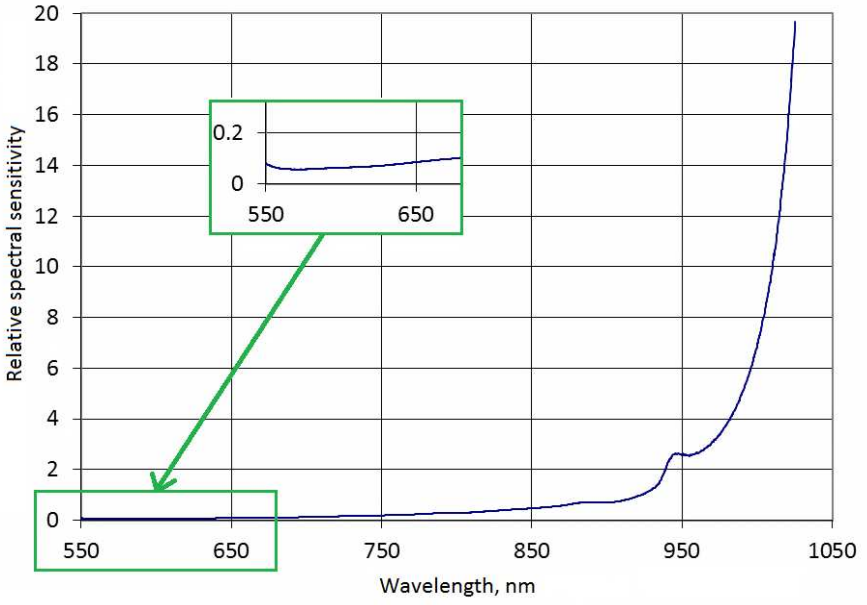


Figure 1. Relative spectral sensitivity of spectrometer OceanOptics USB2000+.

CCD array has some non-linearity of the signal magnitude that can lead to some distortion of the acquired signals. The non-linearity correction of the spectrometer signals was made to avoid this error.

CCD array sensitivity highly depends on acquisition wavelengths. Besides the transmission characteristic of spectrometer optics is also unequal for different wavelengths. This non-uniformity

of the spectral sensitivity leads to distortion of acquired spectra. It is necessary to correct the acquired spectra by spectrometer spectral sensitivity for correct spectra analysis.

Light source of known spectral intensity distribution should be used to determine spectral sensitivity of photodetector, blackbody in our work. The spectrum of the blackbody at some temperature was acquired. Spectral intensity distribution of blackbody at this temperature was calculated according to the Planck's law. The ratio of the calculated Planck spectrum to acquired spectrum is the relative spectral sensitivity of spectrometer (Fig. 1). An example of the thermal spectrum recorded by spectrometer and the same spectrum after correction is shown in Figure 2.

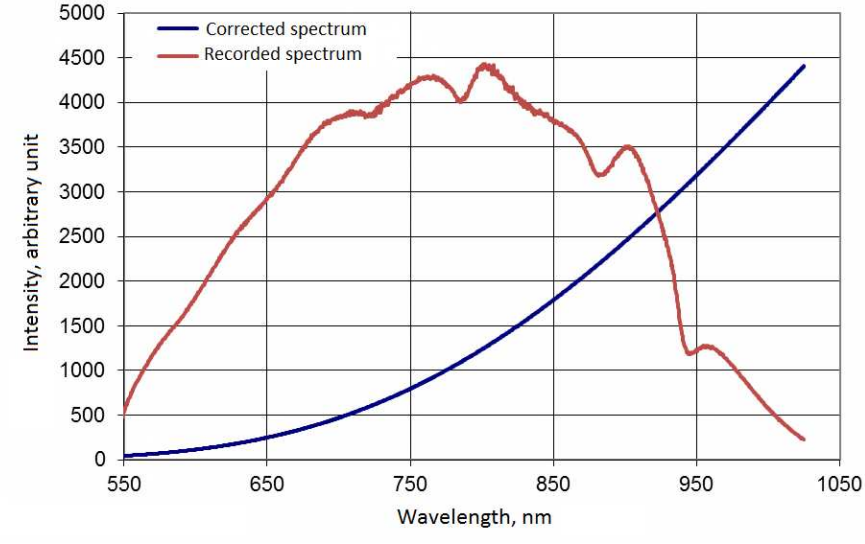


Figure 2. Recorded and corrected spectra.

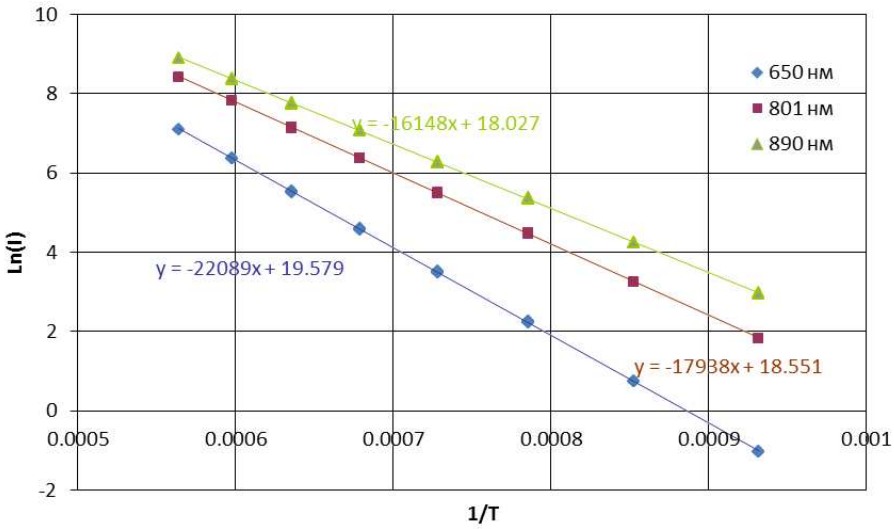


Figure 3. Calibration characteristics of spectrometer at three wavelengths.

Brightness temperature measurement is based on the registration of brightness absolute value of the object surface that requires taking into account the spectrometer sensitivity and the light losses in optical path. Absolute spectrometer calibration by the standard light source should be done to use the spectrometer as the brightness pyrometer. Absolute calibration was performed in the same configuration of the device that was used in the experiment, i.e. with the same optical fiber and with the same collimator adjustment. Calibration was made as follows: the blackbody was stabilized at the temperature in a range of 800°C to 1500°C with the 50°C step. The radiation spectrum was recorded at each temperature. Then a narrow band of spectrum was selected in the vicinity of the wavelength at which it was necessary to measure the brightness temperature, and the average intensity of radiation was determined in this band. Preset temperature was assigned to

acquired average intensity. Calibration curve, as it was mentioned above, must be linear in the coordinates (ln(*I*), 1/*T*), and the slope of this curve must match the average analyzed wavelength. This is the criteria of correct calibration. Figure 3 shows the results of calibration at three wavelengths. The slopes of calibration curves are in good agreement with the corresponding wavelengths.

Using these calibration characteristics it is possible to determine the brightness temperature from the spectra recorded during the experiment. Simultaneous measurement of spectral and brightness temperatures allows determination of the body emissivity at the observation point using formula (6).

## Measurement procedure

Models of blunted cones made of ceramic materials were investigated in the wind tunnel with electric arc heater. These materials are white and this fact determined the problems of brightness pyrometry application for surface temperature measurement of such models.

Before the experiment the absorbance of model material (that is equal to its emissivity) was measured in the laboratory at room temperature by a spectrophotometer SPECORD M40 (Carl Zeiss Iena, GDR) equipped with photometric sphere measuring the absorbance of non-transparent materials. Pressed powder of barium sulfate $BaSO_4$ having reflection coefficient about 98% (but not taken into account in results) was used as a relative standard of matte white surface. The spectrophotometer provides measurements in UV and visible spectral range up to the wavelength of 0.9μm. Figure 4 presents spectral emissivity of two samples. It can be seen that these white samples have very low absorbance (about measurement accuracy), and, taking into account the reflection coefficient of reference sample, the relative error of emissivity determination can exceed 100%. It should be noted that at wavelengths higher than 650 nm the emission coefficient is practically independent on wavelength. It means that in the wavelength range from 650 to 900 nm the investigated material can be considered as a gray body that provides the possibility to measure its spectral temperature.

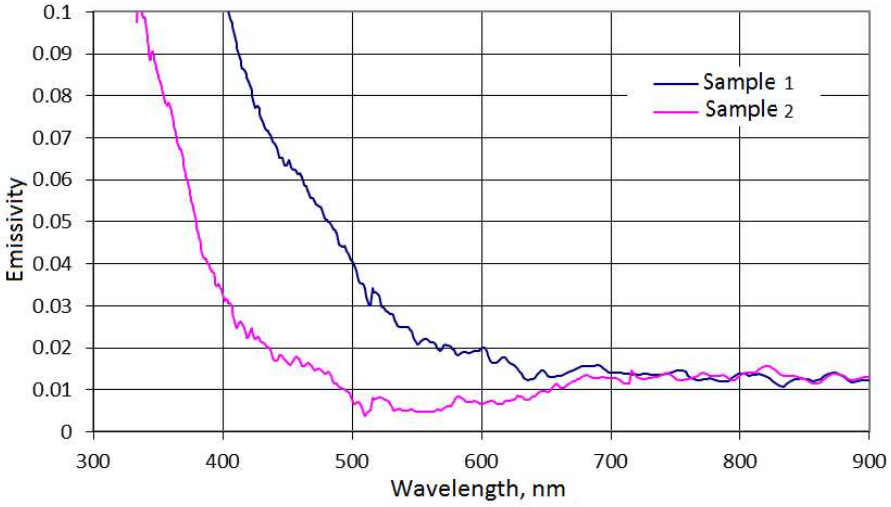


Figure 4. Emissivity at room temperature.

The experimental setup layout is shown in Figure 5. The air is heated to the desired temperature by electric arc. Heater electrodes are made of copper. Erosion of electrodes takes place in the electric arc, so the copper ions appear in the flow and later they are partially oxidized. During the experiment copper ions and copper oxides are deposited on the model surface that changes the color of the model from copper to dark brown and changes significantly the emissivity of the model surface.

Wind tunnel starting time is quite long, so the model is out of flow at the beginning of the experiment to avoid the effect of transient flow. The model is introduced into the flow after reaching the desired flow mode.

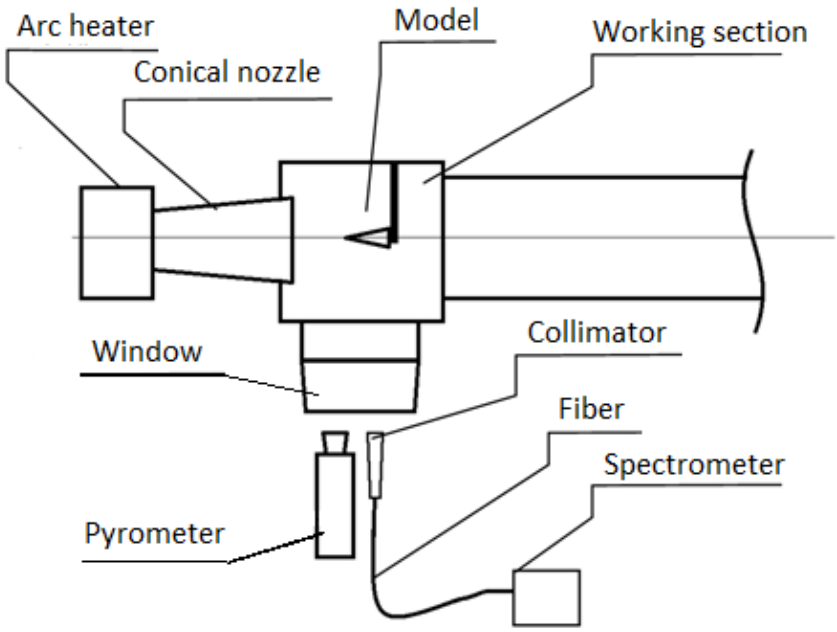


Figure 5. Experimental setup layout.

During the experiment the model is observed through the windows on which the brightness pyrometer and collimator of spectrophotometer were installed. Digital CCD camera (VideoScan, Russia) was used as brightness pyrometer. Narrow-band filter centered near 890 nm was installed on camera lens. After installation and adjustment the pyrometer was calibrated by temperature tungsten lamp SI-10-300. Camera control was performed by the personal computer installed in the control room of the wind tunnel.

Collimator projecting measurement spot to the fiber was mounted near the brightness pyrometer. Collected light was transmitted to the spectrometer through the optical fiber. Spectrometer was calibrated in the laboratory using the blackbody "MIKRON M335". Additionally the transmittance of wind tunnel window was measured and was taken into account during determination of brightness temperature from spectrometer data. Spectrometer was controlled by a separate computer installed in the control room also.

As was mentioned above, the conical models with blunted noses made of white material we investigated. Before the experiment the measurement spot of spectrometer was adjusted on the model nose. The optical fiber connecting the collimator and the spectrometer was disconnected from the spectrometer, white light was entered into the fiber and the light spot was adjusted to the desired region of the model. Then the radiation from infrared LED (890 nm, light passed through the filter of pyrometer) was entered into the fiber and the position of the measurement volume (IR "spot") was acquired by the brightness pyrometer. This procedure allows to combine the results of brightness temperatures, measured by pyrometer and by spectrometer.

Brightness of model surface increases dramatically during the heating, as a result the dynamic ranges of pyrometer and spectrometer are insufficient for registration of such significantly changing signal. Sensitivities of the pyrometer and the spectrometer were changed by varying the exposure time (signal integration time) by hand during the experiment. This approach allows expanding the dynamic ranges of devices significantly, and the exposure time is easily controlled, well-repeated and easily considered in data processing.

At the beginning of the experiment the exposure time was set for the intensity corresponding to the temperature of 600°C. Brightness pyrometer acquired images with a frequency of 1 frame per second. The spectrometer was triggered in external synchronization mode by pulses from pyrometer. Operators controlled the level of the signals on the computer monitors and reduced the exposition time when maximum signal level approached the upper limit.

## Experimental results

As was mentioned above, model surface was initially white. During the experiment copper and its oxides were deposited on the models surface and model gets copper-brown color, the color changed along the length of the cone. Deposition of ions and copper oxides on the model led to emissivity increase. Copper and copper oxides were carried away from the surface of the model with surface temperature increase. As a result, the model nose became white and it led to emissivity decrease. Figure 6 shows the model (temperature field) at different moments of the experiment with the marked position of spectrometer measurement volume. After the model nose had been heated to a certain temperature the material destruction began and it led to the formation of foamed material as a white "mushroom" body. The temperature in Figure 6 was calculated for emissivity 0.8 corresponding to the "sooty" surface. It should be note that the brightness of the white nose is equal to the brightness of "sooty" surface. Since the emissivity of the white spot was few times smaller than the emissivity of the "sooty" surface, the temperature of the model nose was few hundred degrees higher than the lateral surface temperature.

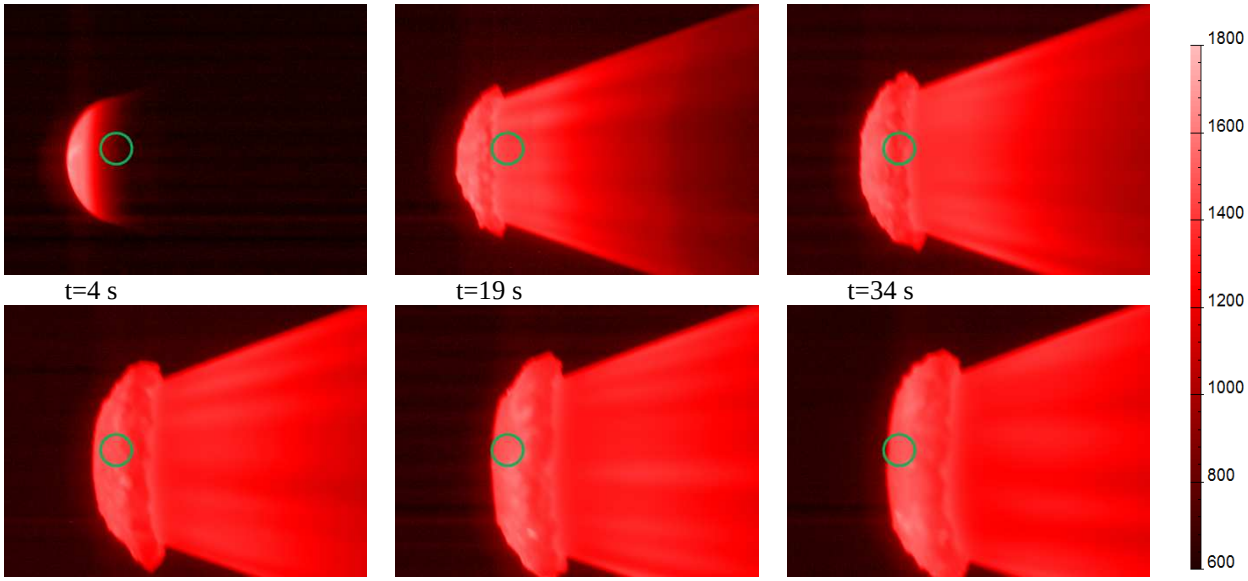


Figure 6. Model images at different moments recorded by brightness pyrometer with marked position of spectrometer measurement volume.

Comparison of brightness temperatures measured by pyrometer and by spectrometer is shown in figure 7. The brightness temperature of spectrometer was determined at the wavelength of 890 nm corresponded to the brightness pyrometer wavelength. These plots allow to estimate the accuracy of brightness temperature measurements since brightness temperatures were obtained using two different devices with different calibration methods. Agreement between the results of measurements performed by two different methods should be considered as good.

Figure 8 shows the results of the measurements of the spectral and brightness temperatures obtained by the spectrometer. Spectral temperature adequately reflects the process of model heating during experiment, while the brightness temperature do not increase and it even fall sometimes at the end of experiment.

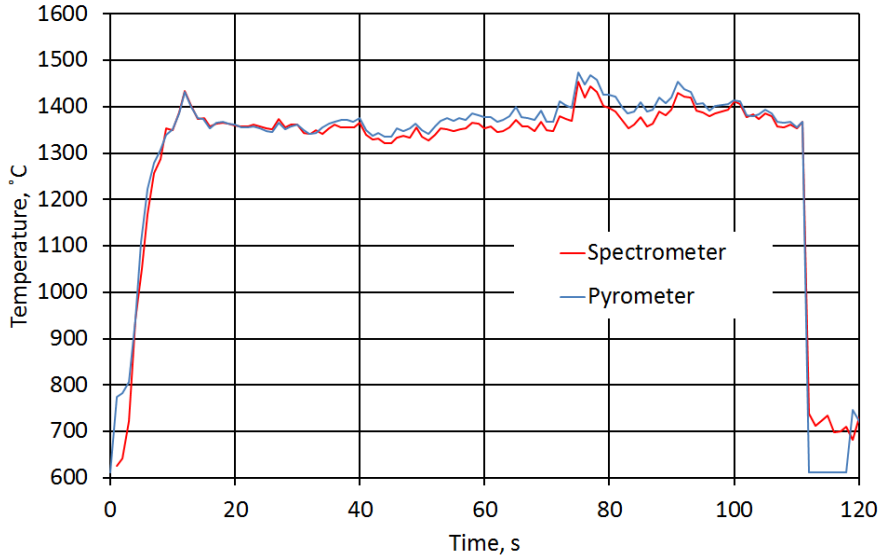

Figure 7. Comparison of brightness temperatures measured by pyrometer and by spectrometer.

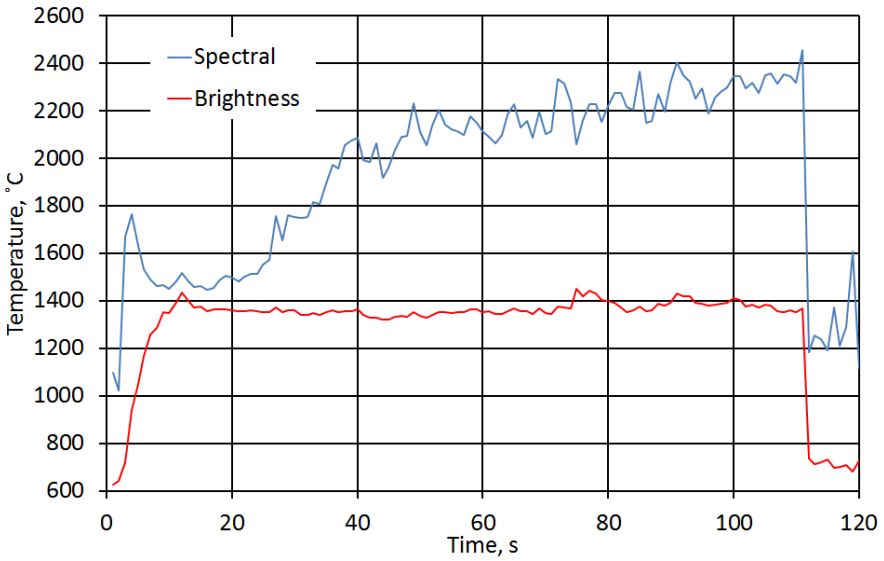

Figure 8. Brightness and spectral temperature changing in time.

Simultaneous measurement of the spectral and brightness temperatures allowed to determination the emissivity changes during the experiment (see Figure 9). The curves correspond to the processes occurring on model in the flow. Since the model was originally "white", it reflected the arc heater light penetrated through nozzle from the plenum chamber, as a result the obtained spectral temperature is high in the first few moments, until the model is not heated. As the model is warming-up, the intensity of model radiation becomes much higher than the light from the plenum chamber, and the spectral temperature approaches to the surface own temperature. During the experiment copper is deposited on the model surface and is partly oxidized. Emissivity increases. At further temperature increase the deposited copper oxides are carried away from the model surface and, as a result, model nose becomes white. Then the measuring volume occurs on the white surface and it leads to emissivity decrease. The resulting emissivity value of the white material is 0.03-0.04 that corresponds to material absorptivity values obtained in laboratory and proves that the error of laboratory measurements of such small values of emissivity is critical for the brightness pyrometer. The combination of brightness and spectral pyrometers allows to control the changes of emissivity

at least at one point of the model and to improving the accuracy of temperature measurements by brightness pyrometer.

It should be noted that the "foamed" white surface works as light-scattering medium. In particular, this medium successfully scatters the radiation from "sooty" lateral surface that penetrates into the model. Since the "sooty" lateral surface radiates essentially intensively, the contribution of light scattered within the model can be quite essential in comparison with the own radiation of the white nose. Unfortunately, it is not possible to take into account the contribution of scattered radiation correctly.

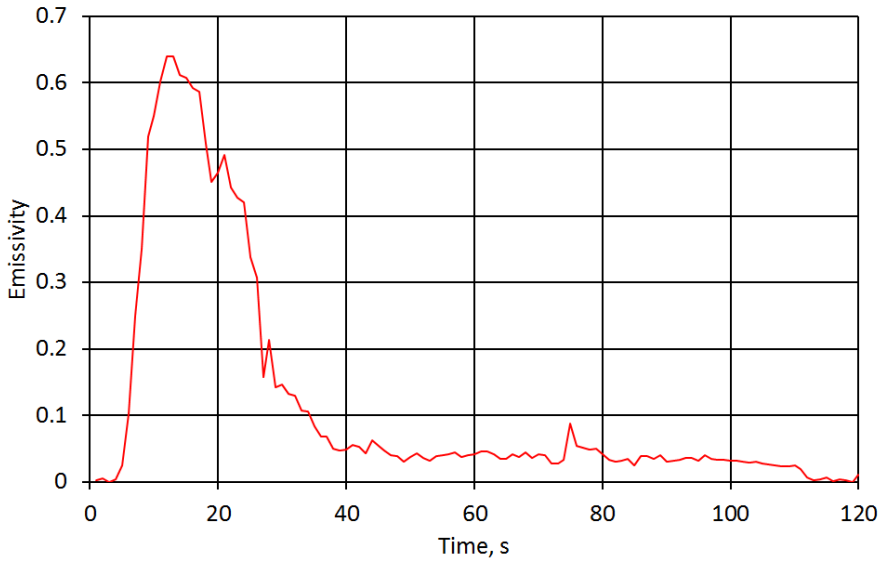


Figure 9. Emissivity changing during the experiment.

## Conclusion

Measurement of surface temperature of white bodies by means of brightness pyrometry faces the problem of accurate measurement of very low values of emissivity. Even quite small absolute error of emissivity determination of such bodies leads to a very significant error of surface temperature measurements. Thus, it becomes necessary to control the emissivity of white bodies during the experiment.

Spectral pyrometry method allows to determine the surface temperature of gray bodies without information about their emissivity. Absolute calibration of spectrometer allows to measure the brightness temperature also. Knowledge of the brightness and spectral temperatures allows to determine the emissivity of the body.

Another advantage of spectral pyrometry is the possibility to measure model emissivity during the experiment. The results of emissivity measurements during the experiment can be used in processing of the results of brightness pyrometer measurements and it will increase the accuracy of temperature measurement.

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