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Spectral radiate characteristics of gas phase combustion product of energetic fules

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Abstract. The results of long-term experimental studies of the spectral radiation characteristics of the gas phase of the combustion products, performed on measuring complexes of medium and high spectral resolution in the temperature range 200-2800 K, are carried out. The spectral transmission functions are parametrized by the two-parameter equivalent mass method, which makes it possible to solve radiation heat transfer problems in structurally inhomogeneous high-temperature multicomponent gas environments of the products of combustion of energy fuels of the combustion chambers of energy units to generate thermal and electrical energy. The results of modeling radiation heat transfer in combustion chambers and heat exchangers of multi-chamber furnaces with hearth multi-row burner devices and bottom feeding of solid fuel combustion products into a radiation heat exchanger from cyclone furnaces are discussed.

1. Introduction

The problem of radiation factors and their effect on radiation heat transfer in high-temperature environments is central to the development of modern technologies for the production of thermal and electric energy in the energy sector, in the industrial industry, and in aerospace engineering. Ensuring a stable pace of economic development and increasing global competitiveness of key industries requires the accelerated development of energy as a means of ensuring the development of production. The contribution of scientific and technological progress to economic growth becomes decisive, since its introduction leads to the effective distribution of the contribution of capital, saving land resources and labor costs. A comprehensive approach to the consumption of resources aimed at developing industries that provide not only the country's defense capabilities, but also the solution of a set of socio-economic problems that require a shift in scientific and technological policy towards sustainable growth in the production of services in order to improve the quality of life, comes first. [1,2].

The effectiveness of functioning is largely determined by the state and level of development of engineering and technology. In many respects, the competitiveness of most goods produced in the country depends on the state of the energy industry. In this regard, optimization of structures in power engineering is in the first place, which can be done by numerically simulating radiation heat transfer in newly developed or reconstructed power plants. In this paper, we consider the results of many years of comprehensive studies of the radiation characteristics of the ingredients of the gas phase of combustion products [1-10], obtained experimentally in a wide temperature range of 200-2800 K and numerical simulation data based on high-temperature atlases of spectral line parameters [10-12]. The spectral range of studies is 0.2–40 µm; equilibrium and nonequilibrium radiation processes are studied [2-4]. The results of these studies can be used not only in industrial energy, but also in renewable energy, solar heat and electricity, as well as in hydrogen energy.

2. Technique and technology for measuring the spectral transmission function

The main radiation characteristic of the gas phase of the products of fuel combustion is the function of spectral transmission (FST) for radiation sources. If the source of spectral radiation is a completely black or "gray" body, then for it the FST is designated $\tau_{\lambda n}$. If the source of radiation is a gaseous medium, then for it the FST $\tau_{\lambda s}$ differs from $\tau_{\lambda n}$ due to the acute selection of the gas phase of the combustion products [12]. With increasing temperature of the combustion products, the fine structure of the gas ingredients and their FST change. The rigorous technology for calculating the FST τ_{is} for the ingredients i of the combustion products can be performed by numerical simulation using high-temperature atlases of spectral line parameters [4,9,12], implemented for the emission of air carriers [12] in the atmosphere. For FST monochromatic radiation:

$$\tau_{\lambda S} = \prod_i \tau_{i\lambda S} \, , \; \tau_{\upsilon S} = \prod_i \tau_{i\upsilon S} \, , \tag{1}$$

where υ is the wave number.

For the spectral resolution $\Delta\lambda$ ($\Delta\upsilon$), the FST is determined by the relation

$$\tau_{\Delta\upsilon S} = \int_{\delta\upsilon} \tau_{\upsilon S} d\upsilon \, , \tag{2}$$

where $\Delta\upsilon$ is the spectral resolution of the monochromator, δ_υ is the spectrometer hardware function.

Calculation $\tau_{\Delta\upsilon S}$ by numerical simulation method, even with the use of supercomputers, is very laborious and requires the development of a special computing technology [11] that provides the necessary accuracy. In this regard, approximate methods for calculating the FST $\tau_{\Delta\upsilon S}$ have been developed, which are based on experimental data. The transfer of thermal radiation is affected only by optically active ingredients of the combustion products that absorb radiation: H_2O vapors, carbon dioxide CO_2, sulfur oxides SO_2, SO, SO_3, nitrogen oxides NO, NO_2, N_2O, N_2O_4, carbon monoxide CO. O_2 and N_2 have only pressure-induced absorption bands and they affect on the optical characteristics of the combustion products through a mechanism for measuring spectral absorption (radiation) lines of optically active ingredients. At the same time, experimental installations for measuring the FST of combustion product ingredients should have full metrological support for monitoring the composition of combustion products and their temperature. Particular attention in the measurement of FST is given to spectral optical methods for measuring the temperature and composition of the radiation propagation medium [2].

The development of methods for calculating the FST requires setting up comprehensive studies of molecular absorption characteristics experimentally at various temperatures, pressures, optical path lengths and recording absorption spectra (radiation) with high, medium, and low spectral resolution Δ. To obtain experimental data on the FST, laboratory complexes of equipment [2,4-8] are used that provide simulation of media in various conditions, including at high temperatures and flames. During measurements, metrological control of the state of the medium under study and the purity of the experiments were provided.

The first measurements of the molecular absorption spectra of radiation by one of the authors in 1964 after the development in the USSR of the MPC-1 multi-pass cell for studying the ingredients of the gas phase of the atmosphere and the products of combustion of automobile and aircraft engines into the atmosphere. As the spectrometry technique has developed, the measuring complexes with the MPC-1 have been improved in order to increase the accuracy of measurements, spectral resolution and expand the functionality. Subsequently, MPC-1 in combination with spectra was used as an analytical laboratory to determine the ingredient composition of the combustion products of various fuels. Providing initial data for developers of civilian and military thermal imaging and aerospace systems required expanding the spectral and temperature range of studies of radiation characteristics to temperatures of 2500-3000 K, new high-temperature flame measuring complexes [2,3]. The use of a working chamber with a multi-way radiation transmission scheme allows you to change the optical path length (measurement sensitivity) during the measurement. The pressure range in the working chamber can be expanded by diluting the sample with an inert optically inactive gas. High spectral resolution allows the identification of the components of the combustion products by the fine structure of the absorption spectra.

To obtain the spectra of reference metrologically supported gas components, a two-beam measuring complex based on the IKS-24 spectrometer [9] is used that allows direct registration of the FST without further processing. A two-beam gas cuvette is two exact copies of each other multi-way cuvettes assembled in a single complex with the same design and control of their work and independent systems evacuation.

Measuring complexes for high-temperature measurements and measurements at high pressures are described [2,5]. Replaceable windows of working ditches provide a spectral range of measurement of FST in spectral region 0.2-100 μm. The optical part of the IKS-21 and IKS-31 spectrometers is supplemented by diffraction gratings with a number of strokes N = 600, 300, 100 mm-1, operating in the first and second orders, interference light filters for apportionment of to highlight the operating orders of diffraction gratings. High-temperature cuvettes with electric heating provide the measurement of the FST of gas media in the temperature range 300 - 1600 K. For the measurement of the FST of gas ingredients at temperatures 3000 > T ≥ 1500 K, hydrogen-oxygen, hydrogen-air, methane-oxygen, methane-air, propane-butane-oxygen, propane-butane-air, acetylene-air, acetylene-oxygen flame. Hydrogen-oxygen flame was used with high spectral resolution in the radiation absorption mode and in the measurement mode of the absolute flame emission spectra.

3. Temperature dependences of the spectral transmission function of the gas ingredients of the combustion products

In the general case, when calculating the FST $\tau_{\Delta\upsilon}$, it is necessary to distinguish the contributions to the absorption due to the wings of the individual spectral lines of the radiation propagation medium, the $\tau_{\Delta\upsilon}^{K}$ induced absorption pressure $\tau_{\Delta\upsilon}^{I}$, the selective absorption of the absorption $\tau_{\Delta\upsilon}^{S}$ spectral lines falling within the selected spectral range (due to the differences in these cases of the dependences of the FST $\tau_{\Delta\upsilon}$ on the absorbing gas content W, pressure P and temperature T). Such a separation allows one to significantly increase the accuracy of the calculation $\tau_{\Delta\upsilon}$ and expand the reliability region $\tau_{\Delta\upsilon}$ (W, P) in terms of the content of the absorbing gas W and pressure P. Then for a given component:

$$\tau_{\Delta\upsilon} = \tau_{\Delta\upsilon}^{K} \cdot \tau_{\Delta\upsilon}^{I} \cdot \tau_{\Delta\upsilon}^{S}, \tag{3}$$

function

$$\tau_{\Delta\upsilon}^{K} \cdot \tau_{\Delta\upsilon}^{I} = \exp\left[-B_{\upsilon k}(T) + B_{\upsilon I}(T)\right] wp \tag{4}$$

where $B_{\upsilon k}(T)$ and $B_{\upsilon I}(T)$ are the coefficients of the continuum and pressure-induced absorption, which depend only on temperature.

To calculate the FST $\tau_{\Delta\upsilon}^{S}$ in planetary atmospheres and high-temperature environments, the pressure in which varies widely, a two-parameter equivalent mass method was proposed in [2].

When calculating $\tau_{\Delta\upsilon}^{S}$, in the general case, the equation:

$$\left(\frac{1}{\ln\tau_{\Delta v}^{S}}\right)^{2} = \left(\frac{1}{\ln\tau_{\Delta v}^{'S}}\right)^{2} + \left(\frac{1}{\ln\tau_{\Delta v}^{''S}}\right)^{2} + \frac{M}{\left(\ln\tau_{\Delta v}^{'S}\right)\left(\ln\tau_{\Delta v}^{''S}\right)}, \tag{5}$$

where

$$\tau_{\Delta v}^{'S} = \exp\left[-k_{v}(T)\omega\right], \tag{6}$$

determines the FST at elevated pressures (P≥10atm) under the conditions of a smeared rotational structure of the absorption spectra.

$$\tau_{\Delta v}^{''S} = \exp\left[-\beta_{v}(T)\omega^{m_{v}}P_{э}^{n_{v}}\right], \tag{7}$$

determines the FST at low pressures P <1atm. The parameter M characterizes the change in the growth rate of the FST during the transition from the region of weak absorption to the region of strong absorption. The parameters K_{v}, m_{v}, n_{v}, $\beta_{v_{c}}$, M are determined from the experimental data. In accordance with the theory of the model representation of the absorption spectra, the equation $K_{v} = \overline{S}/d$

determines the ratio of the average intensity to the distance between the lines, and the value $K_v\Delta v$ characterizes the intensity of the group of spectral line located in the selected interval Δv. To calculate $\tau_{\Delta v}^{S}$ under conditions of an atmosphere inhomogeneous in temperature and pressure, it is convenient to introduce temperature functions:

$$F_{1S}\left(T\right)=\frac{K_v\left(T\right)}{K_v\left(T_0\right)};\ F_{2S}\left(T\right)=\frac{\beta_{vS}\left(T\right)}{\beta_{vS}\left(T_0\right)}. \tag{8}$$

Then

$$-\ln\tau_{\Delta v}^{1S}=K_{vS}\left(T_0\right)W_1;\ -\ln\tau_{\Delta v}^{"S}=\beta_{vS}\left(T_0\right)W_2, \tag{9}$$

where

$$W_1=\int_l\rho\left(l\right)F_{1S}\left[l\left(T\right)\right]dl, \tag{10}$$

$$W_2=\int_l\rho\left(l\right)\left(P\left(l\right)/P_0\right)^{n_v/m_v}F_{2S}^{1/m_v}\left[l\left(T\right)\right]dl. \tag{11}$$

Similarly, for induced and continuous absorption:

$$\beta_{vI}=\beta_{vI}\left(T_0\right)F_I\left(T\right);\ \beta_{v_k}=\beta_{v_k}\left(T_0\right)F_k\left(T\right).$$

The temperature functions $F_I(T), F_k(T), F_{1S}(T), F_{2S}(T)$ used can be represented either in tabular form or in the form of simple analytical approximations, for example, in exponential or power-law form. The parameters of the FST for gas ingredients are tabulated in [1-2].
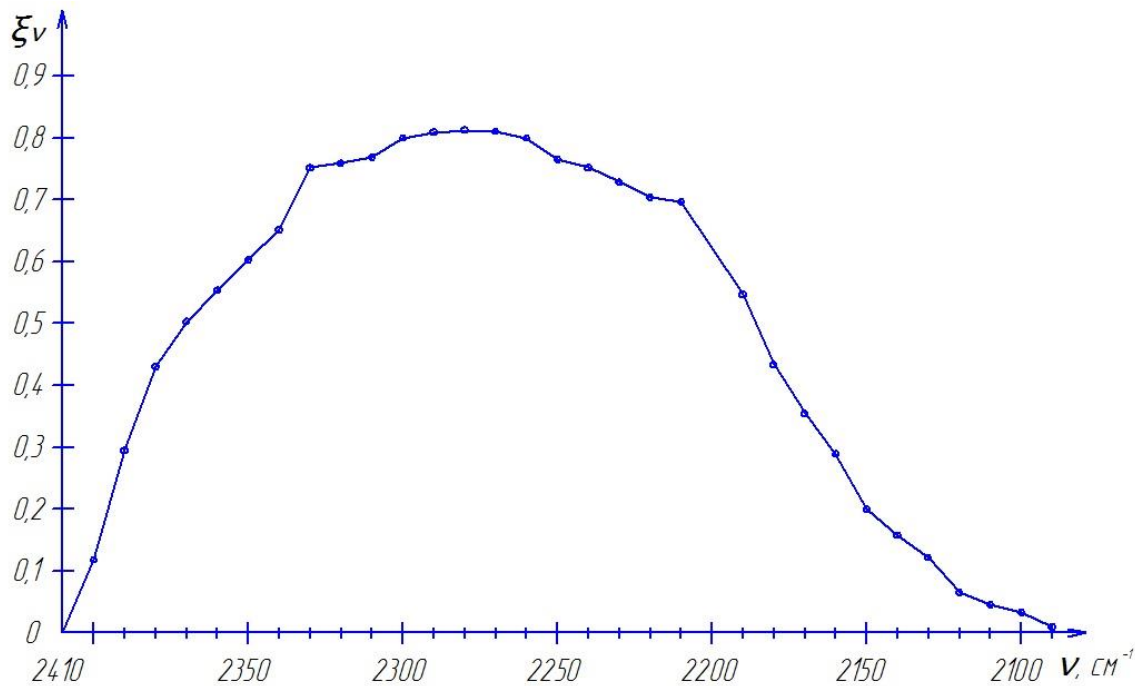

Figure 1. The spectrum of CO_2 emission in a hydrogen-oxygen flame at a temperature of 2300 K in a band of 4.3 µm, at $\omega=0.01$ atm. cm STP and $P_e=1$ atm.

Figure 1 shows the measured emissivity spectrum of ε_λ CO_2 in a hydrogen-oxygen flame at a temperature of T = 2300 K in a band of 4.3 µm. At a wavelength of 4.17 µm, the edge of the v_3 band is observed, beyond which the radiation under these experimental conditions is relatively low in comparison with the radiation of the center of the strip.

The main contribution to the radiation transfer of radiation in combustion chambers for carbon dioxide is made by the bands of 4.3 μm (v_3), 15 μm (v_2) and 2.7 μm ($2v_2 + v_3$, $v_1 + v_3$). The relatively smaller role is played by the 2.0 μm bands ($4v_2 + v_3$, $v_1 + 2v_2 + v_3$, $2v_1 + v_3$); 4.8 μm ($v_1 + v_2$); 5.2 μm ($3v_2$); 9.4 μm ($v_3 - v_1$); 10.4 μm ($v_3 - 2v_2$). Spectral dependences of the absorption coefficient in the band of 2.7 μm CO_2. As the temperature increases, the band broadens to the red region of the spectrum. At high temperatures that are realized in the combustion chambers of energy units for FST CO_2, an approximation of weak absorption is performed (6) and figure 2.

In the combustion chambers of power plants, water vapor has a decisive influence on radiation heat transfer. The parameters of the FST of water vapor were tabulated in [2] in the temperature range 300–2500 K. For small components of the combustion products CO, NO, NO_2, N_2O, the FST were obtained by numerical simulation [10] and their parameterization by the two-parameter equivalent mass method.
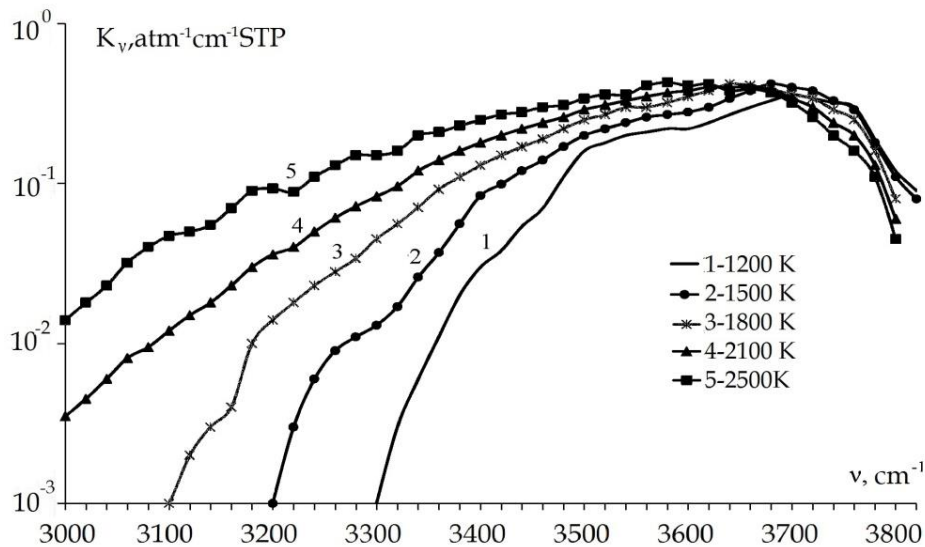

Figure 2. Spectral dependences of the absorption coefficient Kv of carbon dioxide in a band of 2.7 μm at various temperatures.
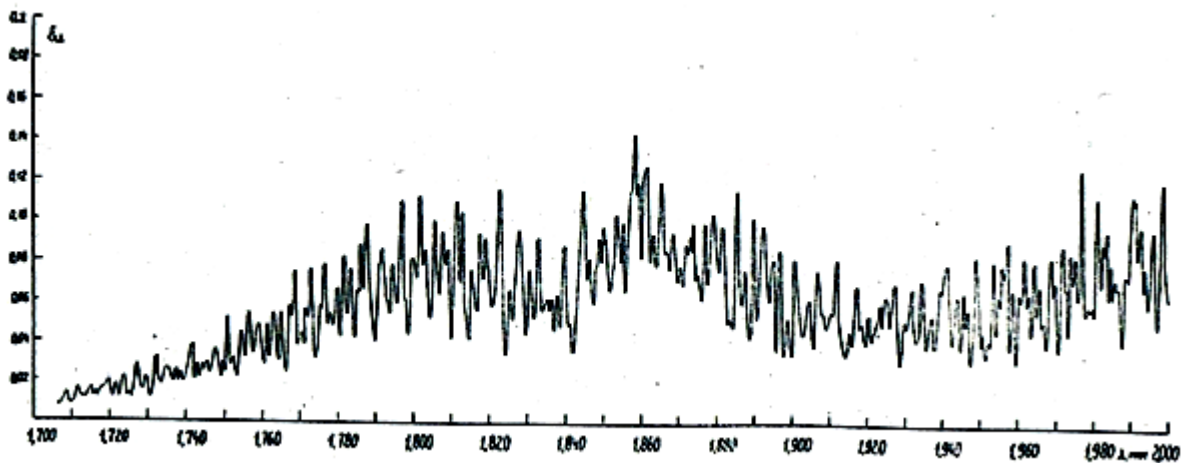

Figure 3. Spectral emissivity of water vapor in the short-wavelength wing of the 1.87 μm band at a temperature of 2400 K, ωH2O = 1.59 atm cm STP, Δν = 1.4 cm⁻¹

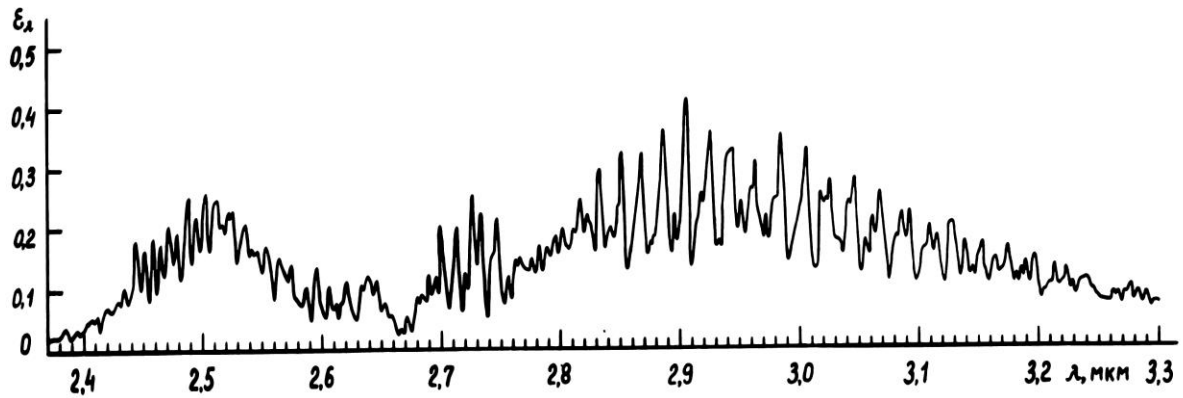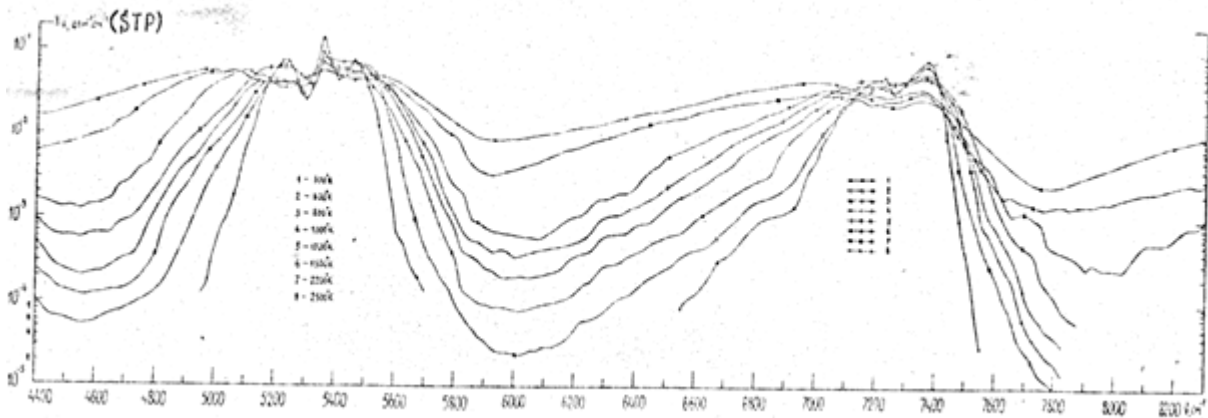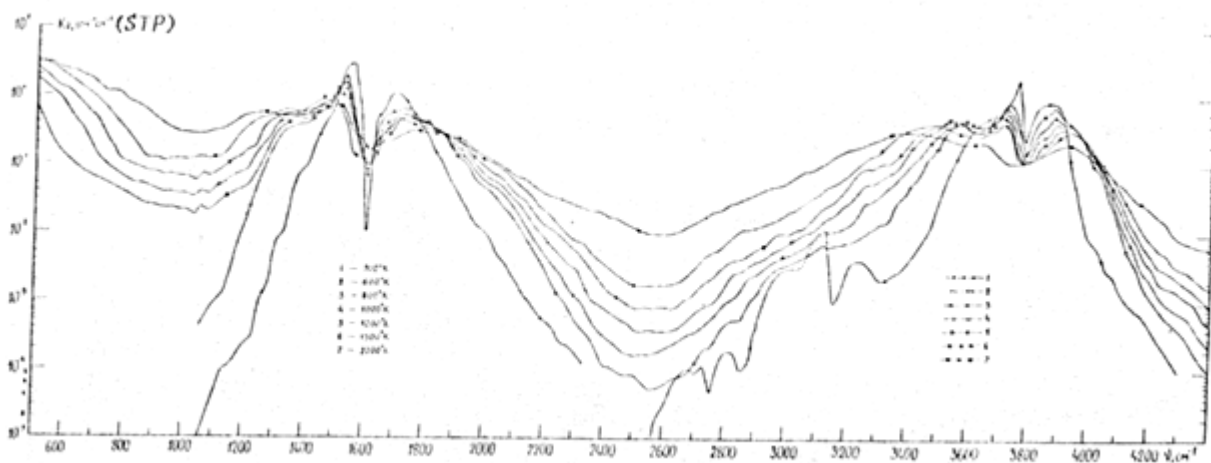**Figure 4.** The spectral emissivity of water vapor in the short-wavelength wing of a 2.7 μm band at a temperature of 2400 K, ωH$_2$O = 2.2 atm cm STP, Δν = 4 cm^{-1}.

a

b

Figure 5. Spectral absorption coefficients of H$_2$O in the bands of 1.87 and 1.38 μm (a); of 6.3 and 2.7 μm (b).

Figures 3-4 show examples of experimental data on the spectral emissivity of H2O vapor in the absorption bands of 1.87 and 2.7 μm.

Figure 5 illustrates the absorption coefficient spectra for various temperatures in the 1.38 absorption bands; 1.87; 2.7 and 6.3 μm.
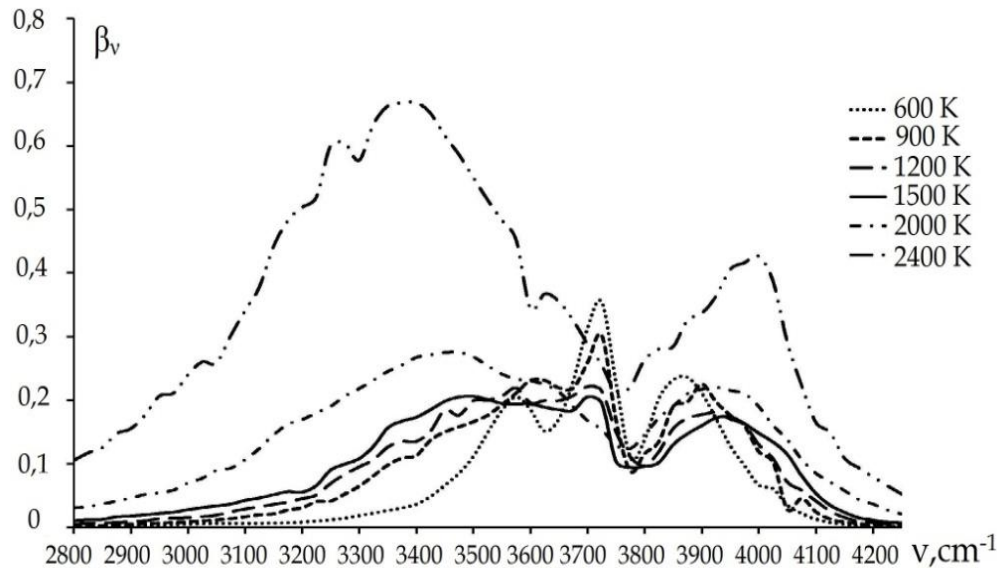

Figure 6. Spectral dependences of the parameter βν of water vapar in the bands 1.37; 1.87; 2.7 μm for different temperatura in region 800-2400K.

Figure 6 shows the dependences of the parameter βν for various temperatures in the bands 1.37; 1.87; 2.7 μm.

4. Conclusion

In conclusion, we dwell on the main results of the research. The results of experimental studies of the function of the spectral transmission of the gas phase of the combustion products of energy fuels in the temperature range of 200-2500 K with high, medium and low spectral resolution are analyzed. The spectral transmission function of water vapor, CO_2, CO, NO, NO_2, N_2O, SO_2 was parametrized using the two-parameter equivalent mass method based on experimental data and numerical simulation of radiation transfer in high-temperature media.

The developed parametrization was applied to solve the problems of radiation heat transfer in the furnaces of energy boilers for the generation of thermal and electric energy [2, 13], including for boiler plants with multi-chamber furnaces for gas and solid fuels. The data obtained are recommended for use in problems of optimizing structural solutions in the development of new power plants and the reconstruction of old ones during their overhaul.

In recent decades, atlases of spectral line parameters of various gas ingredients in the form of an electronic database [15, 16] have been used increasingly to solve the problems of transferring selective radiation from air carriers in the atmosphere [12]. The field of the flame temperature in the atmosphere and the composition of the combustion products are calculated based on reference data on the thermodynamic and thermophysical properties of the combustion products emitted into the atmosphere [14] by rocket engines.

The spectral transmission functions of the atmosphere for selective plume radiation are highly dependent on the type of rocket fuel.

The information obtained on the spectral absorption coefficients for the average spectral resolution [1-10] in a wide temperature range of 200-2500 K and the temperature dependences of the integrated intensities of the vibrational-rotational bands can be successfully used to correct the parameters of the

spectral lines of the ingredients of the gas phase of the combustion products [15-16] in the numerical simulation of radiative heat transfer in structurally inhomogeneous high-temperature media [12].

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