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Transfer Over of Nonequilibrium Radiation in Flames and High-Temperature Mediums

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1. Introduction

Throughout the XX-th century intensive development was received by the high technologies intended for maintenance of stable rates of economic development and global competitive capacity in key industries of manufacture. The contribution of scientific and technical progress in economic growth becomes solving. Now in the developed countries development of high technologies has passed to a stage of the scientific and technical policy directed on introduction of high technologies in sphere of information services, medicine, ecology, power, military-technical manufacture, control of safety of economic activities in any branches of manufacture. Thus the power remains live-providing, a key economic branch in economy of any country and its development should be carried out by advancing rates. On the other hand, the power is a branch in which new scientific and technical achievements take root with high degree of efficiency owing to high level of automation of manufacture and energy transportation.

In the present chapter of the monography basic aspects of a problem of the transfer over of radiation in high-temperature mediums and flames and their decision with reference to problems of remote diagnostics of products of combustion in atmospheric emissions and top internal devices are considered. The special attention is given the account of nonequilibrium processes of radiation which are caused by chemical reactions at burning fuels and photochemical reactions in atmosphere. Radiation of high-temperature mediums is selective in this connection the problem of numerical modeling of spectraradiometer transfer function of atmosphere for non-uniform selective sources of radiation which are flame, combustion products of fuel, torches and traces of aerocarriers, combustion products in top internal chambers is considered. Absence of sharp selection of a disperse phase creates possibility of division of radiation of disperse and gas phases and in the presence of the aprioristic information creates conditions of their remote diagnostics (Moskalenko et al., 2010). The developed measuring complexes (Moskalenko et al., 1980a, 1992b) have allowed to specify substantially the information received earlier under radiating characteristics of products of combustion (Ludwig et al. 1973) and to investigate nonequilibrium processes of radiation in strictly controllable conditions of burning (Kondratyev et al., 2006, Moskalenko et al., 2007a, 2009b, 2010c). The developed two-parametrical method of equivalent mass for functions spectral transmission gas components of atmosphere (Kondratyev, Moskalenko, 1977) has

successfully been applied in calculations of radiating heat exchange in high-temperature mediums (Moskalenko, Filimonov, 2001; Moskalenko et al., 2008a, 2009b). The method of numerical modeling of functions spectral transmission on parameters of spectral lines has been used by us for calculations of the transfer over of radiation of torches and traces of aerocarriers in atmosphere and at the decision of return problems of diagnostics of products of combustion by optical methods (Moskalenko & Loktev, 2008, 2009; Moskalenko et al., 2006). Experimental researches of speed radiating cooling a flame are executed by means of calculation of structure of products of combustion (Alemasov et al., 1972) and modeling of radiating heat exchange in chambers of combustion of measuring complexes with control of temperature of a flame by optical methods (Moskalenko & Zaripov, 2008; Moskalenko & Loktev, 2009; Moskalenko et al., 2010).

Measurements of concentration of oxides of nitrogen in flames have shown that their valid concentration much lower in comparison with the data of calculations (Zel'dovich et al., 1947). There was a necessity of finding-out of the reasons causing considerable divergences of theoretical calculations and results of measurements of concentration NO in flames. The reason strong radiating cooling of flames which didn't speak only equilibrium process of their radiation demanded finding-out.

Processes of burning gaseous, liquid and firm fuel have great value in power, and also in technological processes of various industries. At present a principal view of burned fuel in the European territory is gaseous fuel. Partially it is caused by ecological norms and requirements to combustion products. Use of gaseous fuel conducts to reduction of capital expenses at building of thermal stations and boiler installations owing to an exception of expensive filters of clearing of the list of the equipment of station. High heat-creation ability of gas fuel at low operational expenses provides high efficiency of power installations as a whole. A low cost of transportation at use of gas fuel provides its competitiveness in the market. Decrease in losses of heat at its transportation demands creation of small-sized boilers with high efficiency, high thermal stress of top internal space at the raised efficiency that leads to search of optimum design decisions by working out of power installations. Development of rocket technics, creation of space vehicles of tracking their start and support, optimization of systems of detection and supervision demands the data about structural characteristics of torches both spectral and spatial distribution of their radiation which can be received by correct methods of the decision of problems of a transfer over of radiation and radiating heat exchange in the torch. All it has demanded performance of complex researches of processes of radiation at burning and its the transfer over to medium which are discussed more low.

2. Radiating characteristics gas optically active components

Experimental researches radiating optically active components in a range of temperatures $220 \geq T \geq 800K$ have been begun in 1964 for the purpose of reception of the initial data for modeling of radiating heat exchange and spectral and spatial structure of radiation natural backgrounds of the Earth and atmosphere and anthropogenous influences on climate change (Kondratyev & Moskalenko, 1977; Kondratyev et al., 1983; Kondratyev & Moskalenko, 1984). The developed measuring complexes allowed to measure spectra of molecular absorption at pressure from 10^{-3} atm. to 150 atm. That has allowed to parameterized functions of spectral transmission of atmospheric components in a spectral range $0,2 \div 40$ μm at the average spectral permission Δv =2-10 cm^{-1}, for atmospheres of the

Earth and other planets. Other direction of researches of radiating characteristics of products of combustion fuels developed in parallel with the first and for the known reasons is poorly reflected in publications. Further we will stop on the analysis of results of researches of radiating characteristics of ingredients a gas phase of products of combustion in a range of temperatures 600÷2500K.

2.1 Measuring devices and results of experimental researches

For the decision of many applied problems connected with the transfer over of radiation of a flame in atmosphere and radiating heat exchange in power installations, data on spectral radiating ability of the various gas components which are products of combustion of flame are required. Independent interest is represented by researches of influence of temperature on formation of infra-red and ultra-violet spectra of absorption or radiation of gas components. Depending on a sort of research problems of spectra of absorption or radiation of gas mediums of measurement it is necessary to carry out or with the average permission $\Delta = 5\text{-}20$ cm^{-1}, or with the high permission $\Delta \leq 0{,}2$ cm^{-1}. In the latter case it is possible to measure parameters of spectral lines and to receive the important information on the molecular constants characterizing vibrational – rotary and electronic spectra of molecules (Moskalenko et el., 1972, 1992). In a range of temperatures 295÷1300 K research of characteristics of molecular absorption it was carried out with use the warmed-up multiple-pass ditches (Moskalenko et el., 1972). Other installation (Moskalenko et el., 1980) allowed to investigate as spectra of absorption and radiation of gases in hydrogen-oxygen, hydrogen-air, the propane-butane-oxygen, the propane-butane-air, methane-oxygen, methane-air, acetylene-oxygen, acetylene-air flames in the field of a spectrum 0,2÷25 μm at temperatures 600÷2500 K, and also to investigate characteristics of absorption of selective radiation of a flame modeled atmosphere of the set chemical composition. Besides, any other component can be entered into a flame, of interest for research.

The Block diagram of experimental installation and design of a high-temperature gas radiator is described (Moskalenko et el., 1972). It includes the lighter, high-temperature absorbing (radiating) to a ditch, system of input of investigated gas and control of their expense, optical system of repeated passage of radiation in a ditch under White's scheme, the block of the gas torches forming two counter streams of a flame in quartz ditch with the heat exchanger for decrease radiating cooling of a flame, coordinating optical prefixes for radiation designing on an entrance crack of spectrometers of reception-registering system with replaceable receivers of radiation PEA – 39A, PEA – 62, BSG – 2, cooled photodetectors with sensitive elements PbS, PbTe, GeCu, GeZn, GeAu, GeAg, germanium bolometer. The spectrum of radiating ability of the high-temperature gas medium is defined by tariroving of a spectrometer on radiation of absolutely black body or normalizing radiation sources. Radiation falling on a reception platform is modulated by the electromechanical modulator with frequency of 11 or 400 Hz (in case of work with PEA and photodetectors). Registration of spectra of radiation was made by spectrometer IRS – 21 or the spectrometers of the high permission collected on the basis of monochromators MDR – 2, DPS – 24, SDL – 1. The last are completed with replaceable diffraction lattices with number of strokes 1200, 600, 300, 150, 75 and the cutting off interferential optical filters providing a working spectral range 0,2 $<\lambda <25$ μm. The limit of the spectral permission of spectrometers made 0,1÷0,2 cm^{-1}. Spectral radiating ability of the gas medium

$$\varepsilon(v,T) = G(v) \cdot \frac{N^0(v,T_\beta)}{B(v) \cdot N^0(v,T)} \ , \tag{1}$$

where T – temperature of the investigated gas medium; $G(v)$, $B(v)$ – recorder indications at registration of radiation from the gas medium (flame) and absolutely black body (ABB); $N^0(v, T_v)$ and $N^0(v, T)$ – spectral brightness ABB at temperatures T_v ABB and T the investigated gas medium.

At work in a mode of absorption of not selective radiation by a flame the radiation modulated by the electromechanical modulator from the lighter is registered. Not modulated radiation of the flame by reception system isn't registered. In the lighter as radiation sources SI lamps – 6 – 100, DVS – 25, globar and ABB with temperature 2500K are used. Radiation from these sources, promodulated by the electromechanical modulator, by means of optical system of the lighter goes in high-temperature absorbing gas to a cell which optical part is collected under White's scheme. The thickness of the absorbing component can change by increase in an optical way at the expense of repeated passage of a beam of radiation between mirrors of system of White. The maximum thickness of the absorbing medium can reach 16 m.

Absorbing (radiating) a cell represents the device executed in the form of established in heat exchanger along an optical axis of the cell two mobile pipes, made of quartz. On a circle of entrance cavities from end faces quartz ditches are located two systems of gas torches (on 6 pieces in everyone) for reception of the hot absorbing (radiating) medium. The internal cavity is filled with two counter streams of a flame. Combustion products leave through a backlash between mobile quartz pipes, the heat exchanger and two unions, located at its opposite ends. Investigated gases can be both combustion products, and other gases entered in a cell and warm flame. For flame creation two various systems of torches are used.

At work about hydrogen-oxygen (hydrogen-air) a flame are used torches of Britske, each of which allows to receive a flame of diffusion type. We will remind that under diffusion flame such flame for which fuel and an oxidizer are originally divided is understood. Fuel and an oxidizer mix up or by only diffusion, or partially by diffusion and partially as a result of turbulent diffusion. For reception the propane-butane-oxygen, the propane-butane-air flame hot-water bottles have been designed and made, each of which allows receiving a flame of Bunsen's type. The flame of Bunsen's type is understood as a flame of preliminary mixed oxidizer and fuel.
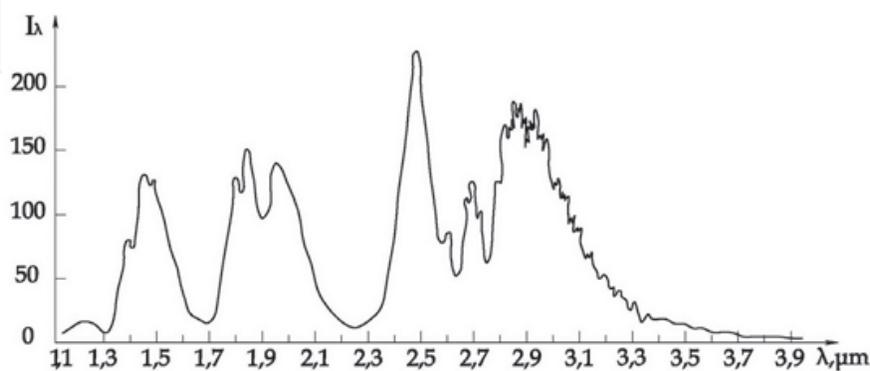

Fig. 1. Radiative spectrum of the hydrogen – oxygen flame at temperature T≈2300K in the range 1,1-4 μm.

Each torch has an adjustable angle of slope of an axis of a torch to an axis of the cell quartz in limits from 20 to 70°. Combustible gases are set fire by a spark. Change of temperature of a flame is reached by change stehiometrical parities of combustible gas and an oxidizer, and also change of combustible gas and oxidizer diluting by buffer gas. Temperature measurement is carried out W – Re and Pt – Po by thermocouples and optical methods.
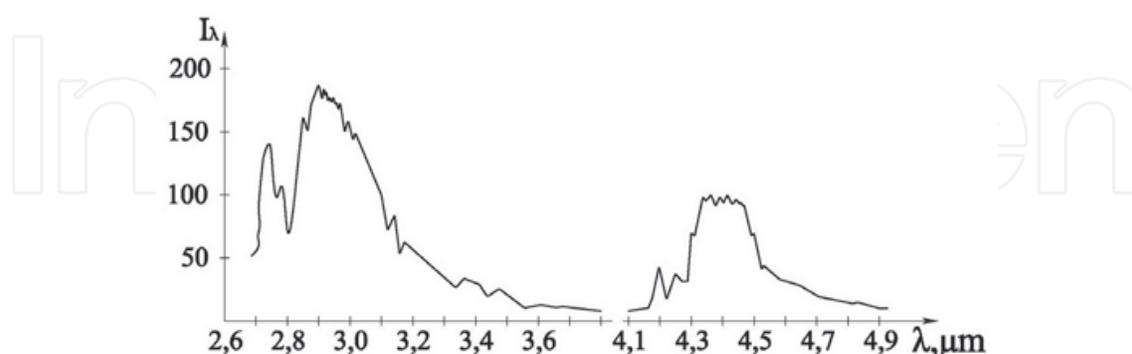
Fig. 2. Radiative spectrum of the hydrogen – oxygen flame in range 2,7 - 5 μm with addition CO_2 in quality of the research gas.

On fig. 1, 2 examples of records of spectra the radiations which have been written down by means of spectrometer IRS–21 are resulted at the average spectral permission at temperature T ≈ 2300K. For oxygen-hydrogen flame radiation bands only water vapor in a vicinity of bands 0,87; 1,1; 1,37; 1,87; 2,7 and 6,3 μm are observed. In ultra-violet spectrum areas are observed electronic spectra of radiation of a hydroxyl OH. With temperature growth considerable expansion of bands and displacement of their centers in red area is observed. At temperatures more 2000K in a flame absence of "windows" of a transparency of a flame, spectral intervals with radiating ability close to zero is observed.

At addition in a flame of gases from a number limit hydrocarbons (methane, ethane, etc.) In radiation spectra bands of carbonic gas (2; 2,7; 4,3; 15 μm) are observed. The similar picture is observed at introduction in a flame and purely carbonic gas. At introduction in flame NO the spectrum of the basic band 5,3 μm NO and a continuous spectrum of radiation NO_2 in a range from 0,3 to 0,8 μm is observed. Data processing of measurements of spectra of radiation of a flame and restoration of a profile of temperature along an axis of an ardent radiator has shown appreciable temperature heterogeneity in zones of an input of a flame in the combustion chamber (Moskalenko & Loktev, 2009) which is necessary for considering at definition of dependence of radiating characteristics of separate components from temperature. This lack has been eliminated in working out of a measuring complex of the high spectral permission (Moskalenko et el., 1992) for research of flames. On working breadboard models of this installation and the experimental sample of this installation the most part of the spectral measurements taken as a principle of parameterization of radiating characteristics of gas components of products of combustion has been executed.

The spectral measuring complex described more low also is intended for registration of spectra of radiation of flames and spectra of absorption of radiation by a flame at the high spectral permission in controllable conditions and has full metrological maintenance. On fig. 3 the block-scheme of this installation is presented. An installation basis make: the block of a high-temperature gas radiator, blocks of optical prefixes 2D-4, intended for increase in an optical way in an ardent radiator and the coordination of fields of vision of the lighter; the

block of a high-temperature radiator of sources of radiation 3 for absolute calibration of a spectrum of radiation of a flame and the Fourier spectrometer of high spectral permission FS – 01. Management of experiment and data processing of measurements by means of software on the basis of measurement-calculation complex IVK – 3. The measuring complex functions in spectral area 0,2–100 µm. Registration of spectra is carried out by means of spectrometers FS – 01, SDL – 1.
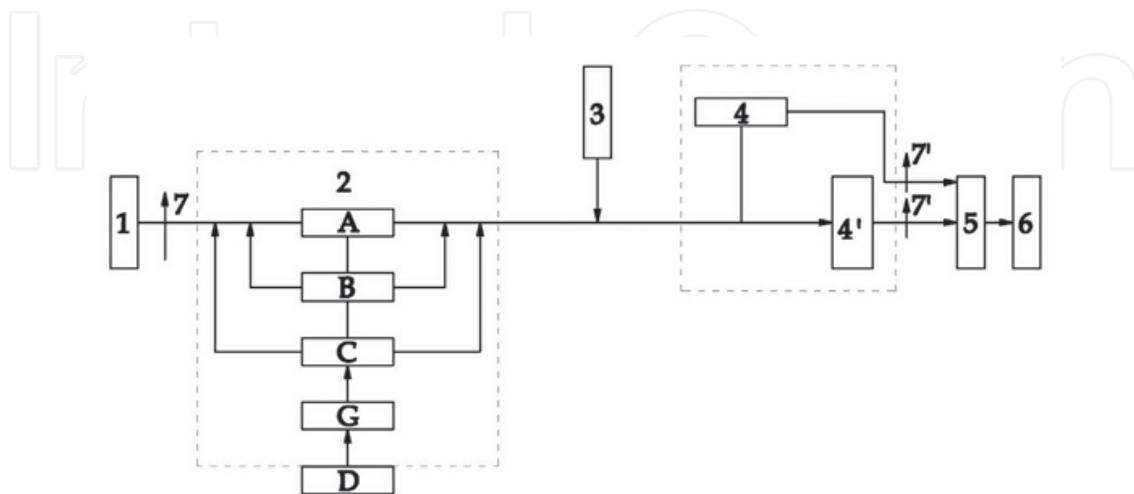

Fig. 3. The experimental installation scheme: 1 – illuminator, 2 – hightemperature gaseous radiator (A – lead – in of research gas system and contrac there expense, B – the mechanism of multiple passing ray thaw a flame, C – the gaseous burner of ascending flow of a flame, G – the gaseous provision system vacuum and control of gaseous expense, D – the system with a water circular pump); 3 – aradiative sources; 4, 4′ – optical system for agreement of in trance and exit apertures; 5 – the reception – recording system; 6 – the system of atreatment of measuring data; 7, 7′ – electrical mechanical modulators of radiation.

The high-temperature ardent radiator structurally represents the block of a gas radiator closed from above by the water cooled cap with two protective windows, stable in time. Formed at burning of gases flames have a squared shape with a size at the basis 40x20 cm². The torch design allows to investigate hydrogen – oxygen, hydrogen – air and hydrocarbonic flames. Measurements have shown that heterogeneity of a temperature field within a field of vision of optical system makes 3 %. Various variants of optical schemes together with system of repeated passage of radiation constructed under White's scheme, allows to investigate radiation spectra of flames and spectra of absorption of continuous radiation of a flame in a range of lengths of an optical way 0,2÷16 m. The flame temperature is measured by a method of the self-reference of spectral lines in lines of water vapor of bands 1, 38 and 1,87 µm. The average relative error of measurement of temperature of a flame makes ±2 %. Measurement of volume expenses of gases was carried out specially graduated rotameters RS – 5. On a parity of mass fuel consumption and an oxidizer the chemical composition of products of combustion are determined by thermodynamic calculation (Alemasov et al.., 1972). To absolute calibration of spectra of radiation of a flame are applied spectrameasured lamps SIRSh 8,5-200-1 and globar KIM, preliminary graduated on metrology provided standards.

Measurement of spectra of radiation and spectra of absorption of radiation by a flame allow to define spectral factors of nonequilibrium functions of a source of radiation in flames. Such

measurements have revealed considerable nonequilibrium source functions in an ultra-violet part of a spectrum of a flame (the factor of nonequilibrium reaches values 20 – 100). At the same time vibrational-rotary spectra of radiation of water vapor in flames remain equilibrium. Nonequilibrium radiations OH in flames is strongly shown in an ultra-violet part of a spectrum and considerably influences radiative transfer over in flames and in vibrational-rotary bands $v_1, 2v_1, 3v_1$, where v_1 – frequency of normal fluctuation OH. The error of measurements of function of a source makes 30 % for an ultra-violet part of a spectrum and 7-10 % in infra-red bands of radiation of a flame. It is found out also nonequilibrium radiations in electronic bands of oxides of nitrogen.

At measurement in a mode of absorption of radiation the flame modulates radiation of the lighter 1. Nonmodulated radiation of a flame doesn't give constant illumination and isn't registered by receiving-registering system. Modulation of radiation of a flame is created by the modulator 7 ′. Registration of spectra of radiation of flames in vibrational–rotary bands is carried out by Fourier spectrometer FS – 01 which reception module is finished for the purpose of use of more sensitive cooled receivers of radiation. The major advantage of the Fourier spectrometer in comparison with other spectrometers – digital registration of spectra with application of repeated scanning of spectra and a method of accumulation for increase in the relation a signal/noise. Prominent feature of Fourier spectrometer is discrete representation of the measured spectrum of radiation of a flame with the step equal to the spectral permission. The last has demanded working out of the software for processing of the measured spectra, restoration of true monochromatic spectral factors of absorption and parameters of spectral lines of absorption (radiation), their semiwidth and intensitys. With that end in view measured spectra are exposed to smaller splitting with step $\delta = \Delta/5$, where Δ – the spectral permission of the Fourier spectrometer. Value in splitting points is defined by interpolation.

Reduction of casual noise is reached by smoothing procedure on five or to seven points to splines in the form of a polynom of 5th degree. The spectrum of radiation received in a digital form is exposed to decomposition on individual components of lines.

From the restored contours of spectral lines it is easy to receive intensity and semiwidth of lines. Thus intensity such Lawrence's lines

$$S_m = \int_{-\infty}^{\infty} K_m(v)dv = K_{vm}\pi\alpha_m , \qquad (2)$$

where K_m - absorption factor in the center of a contour of a line, α_m - its semiwidth, K_{vm} - the restored contour of a spectral line. Thus the condition should be met

$$1 - \int_{-\infty}^{\infty} dv\exp\left[-k_m(v)w\right] = \int_{-\infty}^{\infty} A_{Im}(v)dv , \qquad (3)$$

where w - the substance maintenance on an optical way, A_{Im} - the measured function of spectral absorption of such line. Parameters of spectral lines of water vapor can be used for temperature control in a flame (Moskalenko & Loktev, 2008, 2009).

On fig. 4 the example of the measured spectrum of the high spectral permission of radiation of a flame for spectral area 3020÷3040 cm^{-1} is resulted. On fig. 5, 6 spectra of radiating ability of a flame in vibrational–rotary bands of water vapor are illustrated at the average spectral permission Δv.
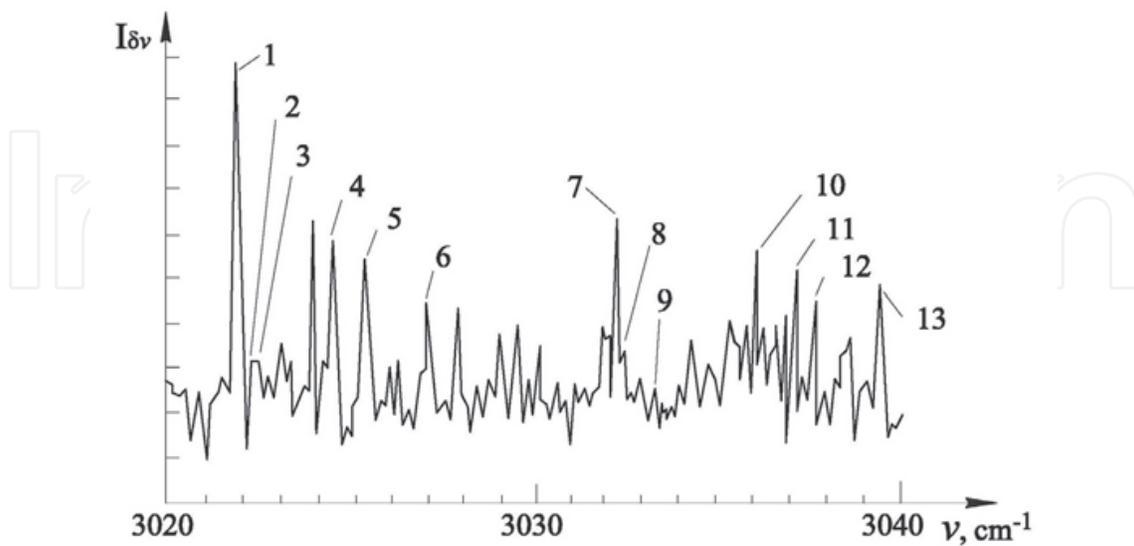
Fig. 4. The record of a high resolution radiative spectrum of the hydrogen – oxygen flame in the range 3020-3040 cm^{-1}. Centers of spectra lines: 1 – 3021,806 (v_1), 2 – 3022,365 ($2v_3$), 3 - 3022,665 ($2v_2$), 4 - 3024,369 (v_1), 5 – 3025,419 ($3v_2 - v_2$), 6 - 3027,0146 (v_1), 7 - 3032,141 (v_3), 8 - 3032,498 ($3v_2 - v_2$), 9 - 3033,538 ($3v_2 - v_2$), 10 - 3036,069 ($3v_2 - v_2$), 11 - 3037,099 ($3v_2 - v_2$), 12 - 3037,580 ($3v_2 - v_2$), 13 - 3039,396 (v_1) cm^{-1}.
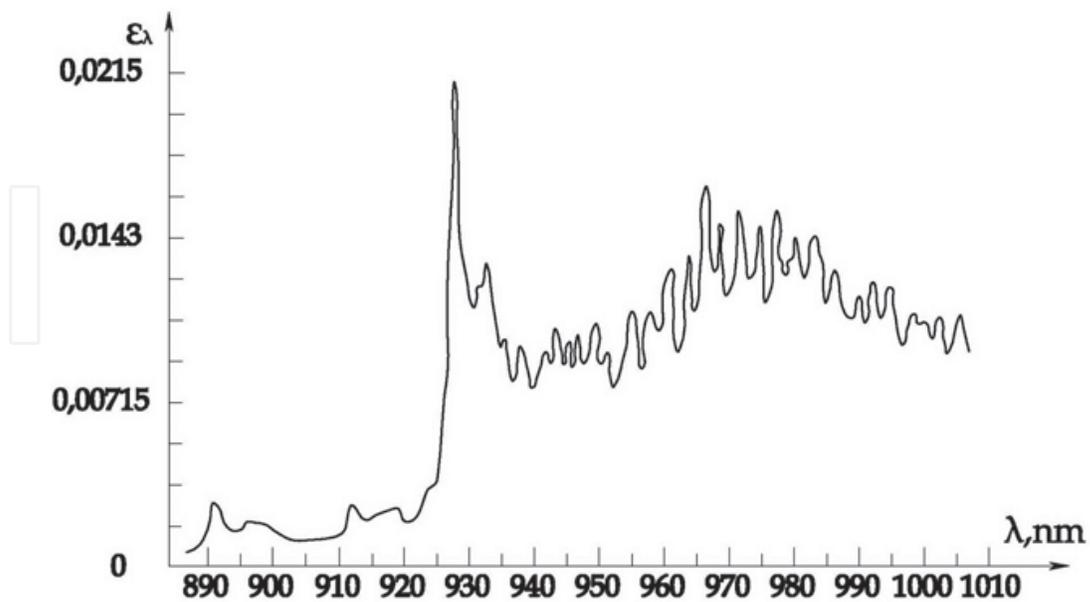

Fig. 5. Spectral emissivity of water vapor at T = 2400K in the band 0,96 μm. ω_{H2O} = 1,59 atm· cm STP, spectral resolution Δv = 10,6 cm^{-1}.
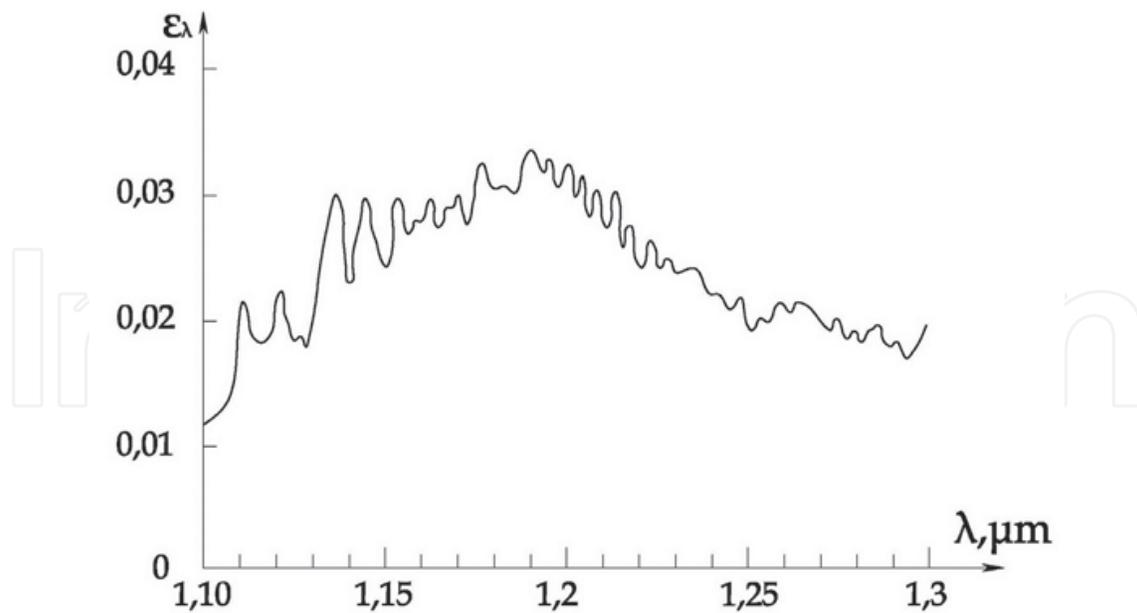
Fig. 6. Spectral emissivity of water vapor in the band 1,14 μm. T = 2400K, ω_{H2O} = 1,59 atm· cm STP, spectral resolution Δv= 15,5 cm^{-1}.

The spectra of radiation of the high spectral permission received in a digital form aren't calibrated on absolute size. Transition from values of relative spectral brightness to absolute radiating ability is carried out on parity

$$A_{\delta v} = \frac{I_{\delta v}(1-\bar{\tau})}{\frac{1}{\Delta v}\int I_{\delta v} dv} , \qquad (4)$$

where $\bar{\tau}$ – average value of function spectral transmission for the processed site of a spectrum Δv. Data on $\bar{\tau}$ have been received by us earlier for various products of combustion of flames. Further difficult function $A_{\delta v}$ it is decomposed to separate components, using a method of the differentiated moments, according to which

$$A(v) = \sum_{m=1}^{M} A_m \left[\sum_{n=0}^{N} A_{mn}\left(v - v_m^o\right)^n \right]^{-1} , \qquad (5)$$

where A_m – a maximum of intensity of such line, A_{mn} - factors of the generalized contour.

$$q_m = \frac{1}{\sum_n A_{mn}\left(v - v_m^o\right)^n} , \qquad (6)$$

Characteristics A_m give the full information on separate contours and are defined as decomposition factors abreast Taylor of some function $f_m(v)$, describing such contour:

$$f_m(v) = \frac{1}{m} \sum_{n=0}^{N} A_{mn}\left(v - v_m^o\right)^n . \qquad (7)$$

Value A_m is a maximum of amplitude of a contour. The center v_m^0 is defined from a condition of equality to zero of factor A_{m1}. Value of semiwidth of a line turns out from a parity

$$\alpha_m = \sqrt{\frac{\sqrt{A_{m2}^2 - 4A_{m4}} - A_{m2}}{2A_{m4}}} \, , \tag{8}$$

Further the profiles received thus are restored on influence of hardware function of a spectrometer. So, we have separate contours of function of absorption $A_m(v)$ from which it is easy to pass to contours of factors of absorption $K_m(v)$:

$$K_m(v) = \sum_{m=1}^{M} K_m\left(v - v_m^0\right) , \tag{9}$$

where M – number of lines in a spectrum, m – line number. On fig. 7 the example of decomposition of function $A_{\delta v}$ on individual contours for oxygen-hydrogen of a flame for a spectrum site 3064÷3072 cm^{-1}, and also comparison (a curve 2) and calculated (a curve 3) on the restored contours of spectral lines of function $A_{\delta v}$ is presented. Integrated intensity of lines were defined from a parity (2). Detailed processing of spectra of radiation of water vapor in flames which has revealed many lines which were not measured earlier has been executed.
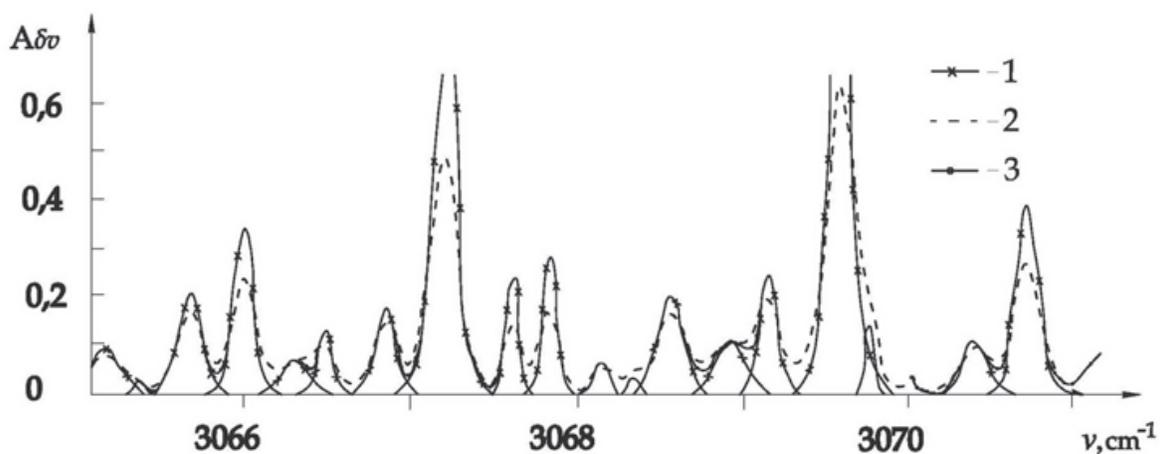

Fig. 7. The expansion of measuring function $A_{\delta v}$ on individual contours. 1 – separate components of expansion, 2.3 – function $A_{\delta v}$ measuring and calculative by reconstituting parameters of spectral lines accordingly.

In table 1 as an example parameters of spectral lines of water vapor are resulted at temperature T = 2100K for spectral ranges 3271÷3274 and 3127÷3130 cm^{-1}. Recalculation of parameters of lines on other temperatures can be executed under the formula

$$S(T) = S(T_o)\left(\frac{T_o}{T}\right)^{1.5} \frac{Q(T_o)}{Q(T)} \exp\left[-1.439E'\left(\frac{1}{T} - \frac{T}{T_o}\right)\right]. \tag{10}$$

Statistical sum $Q(T)$ in the ratio (10) is calculated in harmonious approach. That circumstance pays attention that the centers of spectral lines measured at temperatures of spectral lines T = 2100 K and temperature T_0 = 1000 K don't coincide that is possible, is caused by the displacement of spectral lines caused by pressure, and also temperature displacement of lines. These distinctions in position of the centers of spectral lines surpass often an error of measurements of the centers of lines which in our experiments makes ±0,02 cm^{-1}. The measured semiwidth of spectral lines of water vapor basically will be coordinated with results of calculations under the theory of the Anderson, executed by us at temperatures 300÷3000 K.

ν , cm^{-1}	S, atm^{-1}cm^{-1}	α, cm^{-1}	ν , cm^{-1}	S, atm^{-1}cm^{-1}	α, cm^{-1}
3271,731	0,0131	0,075	3127,8714	0,0123	0,129
3271,944	0,00642	0,084	3128,115	0,0015	0,075
3272,101	0,01272	0,080	3128,395	0,0042	0,081
3272,395	0,00408	0,066	3128,600	0,00216	0,076
3272,654	0,00876	0,168	3128,806	0,00277	0,083
3272,811	0,0114	0,080	3129,109	0,00498	0,092
3273,041	0,0236	0,111	3129,273	0,00387	0,091
3273,436	0,033	0,099	3129,589	0,0154	0,105
3273,735	0,0261	0,092	3129,941	0,0130	0,104

Table 1. Parameters of lines of water vapor at T = 2100 K in the hydrogen-oxygen flame for sites of a spectrum 3271 – 3274 and 3127 – 3130 cm^{-1}. STP.

2.2 Device for modeling of the transfer over of selective radiation in structurally non-uniform mediums

The problem of a transfer over of selective radiation of torches and streams of aerocarriers is put in the sixtieth year of XX th century. The transfer over of selective radiation is influenced by following factors: the temperature self-reference of spectral lines of radiation, displacement of spectral lines with pressure, displacement of spectral lines as a result of high speed of aerocarriers (Dopler's effect), the temperature displacement of the spectral lines which have been found out for easy molecules (vapor H_2O, CH_4, NH_3, OH) (Moskalenko et el., 1992). The executed calculations have shown that displacement of spectral lines with pressure in a flame, making thousand shares of cm^{-1}, and doplers displacement of spectral lines in conditions turbulized high-temperature mediums can't render appreciable influence on function spectral transmission. Temperature displacement of spectral lines in a flame make the 100-th shares of cm^{-1} and at high temperatures reach semiwidth of spectral lines and more. It leads to that radiation of a high-temperature kernel of a torch is to a lesser degree weakened by its peripheral layers that strengthens radiating cooling torch kernels. At registration of radiation of a torch of the aerocarrier the effect of an enlightenment of atmosphere is observed more considerably in comparison with the account only the temperature self-reference of spectral lines. If for the temperature self-reference the spectral effect of an enlightenment is observed more intensively for optically thick mediums the effect of an enlightenment of atmosphere at the expense of temperature

displacement of spectral lines is shown and for optically thin selective radiators and observed by us earlier at registration of radiation of system «a selective radiator – atmosphere» with the high spectral permission in bands of water vapor.

Earlier the problem of the transfer over of selective radiation was put in interests of the decision of problems of the transfer over of radiation of torches and streams of aerocarriers in atmosphere of the Earth (Moskalenko et el., 1984). It has been found out by numerical modeling that law of the transfer over of radiation in low-temperature and high-temperature mediums considerably differ. Burning and movement of products of combustion in a stream is accompanied by wave processes at which there is high-frequency making (turbulence) and low-frequency (whirls). Thus low-frequency wave processes can make the greatest impact on the transfer over of selective thermal radiation while influence of turbulence on the transfer over of selective radiation can be neglected. At high pressures of the non-uniform medium the thin structure of a spectrum of gas components is greased also with influence of sharp selectivity of spectra of radiation on radiating heat exchange it is possible to neglect.

At low pressure and high temperatures of medium effects of temperature displacement of spectral lines in structurally non-uniform mediums can render the greatest influence on the transfer over of selective radiation, not which account for easy molecules (H_2O, CH_4, NH_3, OH) in settlement schemes can essentially underestimate radiating cooling high-temperature zones of a torch (Moskalenko & Loktev, 2009). On the other hand, sharp selectivity of radiation of the gas medium promotes preservation of heterogeneity a temperature field at movement of products of combustion in a fire chamber owing to decrease in absorption of high-temperature zones of its torch by peripheral low-temperature layers.

Creation non-uniform on temperature of the gas medium in top internal space is promoted also by specificity of radiating heat exchange in top internal space, when speed radiating cooling peripheral zones optically a thick torch above, than in its central part. Even if the burning device forms front of products of combustion homogeneous for temperature in process of movement of gases in a plane, normal to a direction of movement of a stream, there is heterogeneity so heterogeneity of a field of temperature becomes three-dimensional.

Modeling of structurally non-uniform gas mediums is carried out by means of the optics-mechanical device in which the amplitude modeled heterogeneities can varies in a range of temperatures 400÷2500 K. On fig.8 the structure of an optics-mechanical part in section and the top view is shown. Installation contains the lighter with a source of modulated radiation, mirror optical system of repeated passage of a bunch of radiation under White's scheme between which mirrors the block of gas torches mounted on a rack with possibility of change of position and an inclination of a cut of a plane of capillaries of torches concerning a plane of the main sections of mirrors of optical system.

The block of gas torches includes the radiator basis in which branch pipes with capillaries accordingly for combustible and oxidizing gases are built in serially. Cooling of branch pipes with capillaries is carried out by means of radiators of water cooling. Behind a target mirror of optical system are consistently established the mechanical modulator – the breaker of radiation and a spectrometer. The gas torch having possibility of moving on height and a turn in horizontal and vertical planes, together with an optical part make an ardent multiple-pass cell which from above is covered with a metal cap cooled by water.
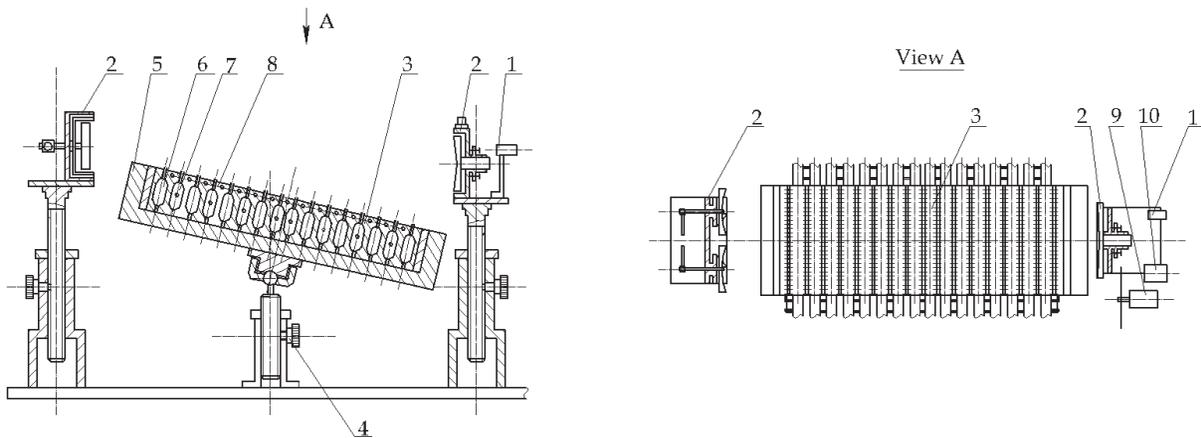
Fig. 8. An optics-mechanical part of a non-uniform radiator: 1 – the lighter; 2 - mirror optical system under White's scheme; 3 - the block of gas torches; 4 – a rack; 5 - the radiator basis; 6 and 7 - capillaries accordingly for combustible and oxidizing gases; 8 – radiators; 9 - the mechanical modulator – the radiation breaker; 10 – a spectrometer.
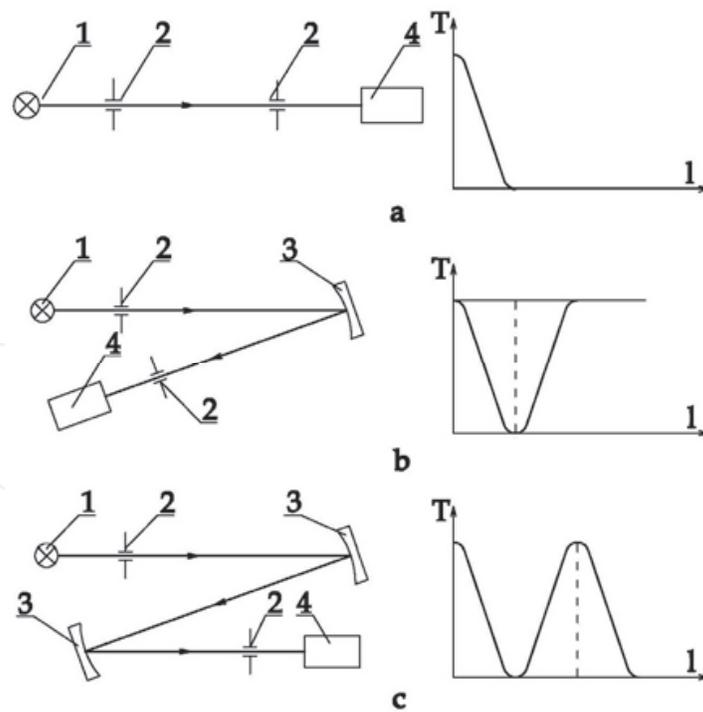

Fig. 9. Formation of profiles of temperature for cases unitary (a), double (b) and triple (c) passages of a beam of radiation through a flame stream. 1 – the lighter; 2 – entrance and target cracks; 3 – spherical mirrors; 4 – the radiation receiver.
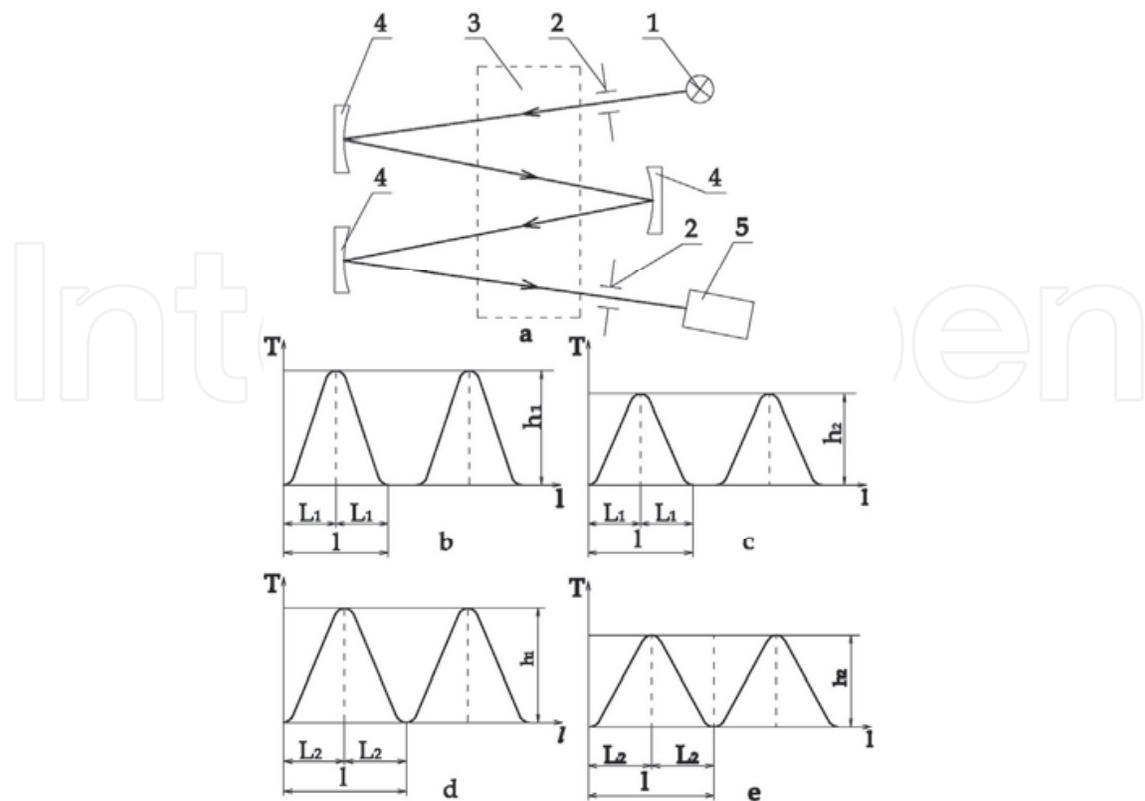
Fig. 10. Formation of profiles of temperature for cases of quadruple passage of radiation through a flame and temperature profiles T corresponding to them on an optical way of radiation l: 1 – a radiation source; 2 – entrance and target cracks; 3 – a flame zone; 4 – mirrors; 5 – a spectrometer.

For preservation of vertical development of a flame at inclined position burning devices on capillaries it is desirable to establish nozzles with a turn corner (π – α), where α – a corner of a plane of a cut of capillaries burning devices concerning a horizontal plane. On fig. 9 the kind of temperature profiles for various cases of passage of radiation along an optical way through ardent multiple-pass cell is shown. When the plane of a cut of capillaries of a torch is parallel to a plane of the main sections of mirrors of optical system, the bunch of radiation of the lighter passes through the gas medium homogeneous for temperature. Changing height of position of a gas torch, in this case probably to define distribution of temperature depending on height over a plane of cuts of capillaries. Further this information can be used for definition of a profile of temperature non-uniform on temperature of the gas mediums modeled in installation «a non-uniform gas radiator». Optical schemes are presented in the left part of drawing, and temperature profiles T on an optical way l – in the right part of drawing.

Mirror reflection of these profiles (return temperature profiles) can be received by return turn of a plane of a gas torch concerning a horizontal plane. On fig. 10 the explanatory to formation of profiles of temperature for cases of quadruple passage of radiation through a flame and temperature profiles T corresponding to them on an optical way of radiation l is presented. Radiation from a radiation source through an entrance crack passes a flame zone, is reflected consistently by mirrors after quadruple passage through a flame zone projected on a target crack of receiving-registering system of a spectrometer. Depending on constructive length L zones of a flame along an optical way and height h arrangements gas

burning devices over the basis change (to look fig. 10) amplitude of temperature heterogeneity and its half-cycle Δl. On fig. 10 cases are presented, when $h_1 \neq h_2$ and $L_1 \neq L_2$.

For homogeneous system the law of Kirhgof is carried out. In non-uniform medium on structure it is broken, and function spectral transmission in a spectral interval of final width becomes dependent as from thin structure of a spectrum of the radiating volume, and from thin structure of a spectrum of the absorbing medium. Effects of display of sharp selection of spectra of radiating and absorbing mediums on function spectral transmission lead to certain features of radiating heat exchange in a torch and transfer function of distribution of radiation of a torch in medium. So radiation of a kernel of a torch is to a lesser degree weakened by its peripheral layers. In chambers of combustion it leads to increase heat-receptivity by surfaces of heating at the expense of radiating heat exchange, and at distribution of radiation of a torch of the aerocarrier to atmosphere the effect of an enlightenment of atmosphere when atmosphere becomes more transparent for non-uniform high-temperature selective radiators, in comparison with not selective radiators is observed. Consideration of process of the transfer over of selective radiation in atmosphere allows constructing the following scheme of its account through the factors of selectivity defining the relation of function spectral transmission for selective radiation τ_c to function spectral transmission for not selective radiation. If to enter factor of selectivity for a component i:

$$\eta_{i\lambda c} = \frac{\tau_{i\lambda c}}{\tau_{i\lambda n}}, \qquad (11)$$

Then full transmission of mediums for selective radiation $\tau_{\lambda c}$ it is represented in a kind:

$$\tau_{\lambda c} = \prod_i \eta_{i\lambda} \cdot \tau_{i\lambda n} \qquad (12)$$

As functions $\tau_{i\lambda n}$ are studied, researches $\tau_{\lambda c}$ is reduced to reception of sizes $\eta_{i\lambda}$ as functions of temperature, an optical thickness of radiating and absorbing mediums, and also pressure which can be defined on the basis of experimental researches or the data of numerical modeling of the transfer over of radiation on thin structure of a spectrum of radiating and absorbing mediums (Moskalenko et el., 1984).
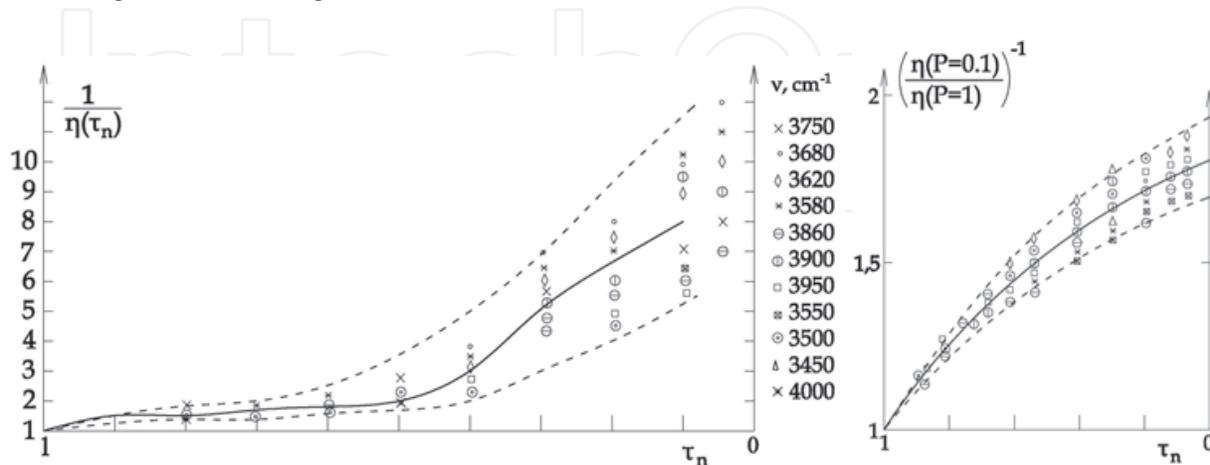

Fig. 11. Dependence of factor of selectivity on function spectral transmission at various frequencies.

The executed experimental researches and results of numerical modeling have shown that sizes $\eta_{i\lambda}$ depend on temperature. At low temperatures of selective radiators, for example streams of turbojets, sizes $\eta_{i\lambda} \leq 1$ and selective radiation is absorbed in atmosphere more intensively than not selective radiation. To calculations of function spectral transmission for not selective radiation it is applied one-parametrical and two-parametrical methods of calculation of the equivalent mass, discussed more low.

Dependence of transfer function on structure of absorbing and radiating mediums is important for considering in problems of remote diagnostics of products of combustion by optical methods and supervision over aerocarriers on their infra-red thermal radiation. The importance of the account of effect of selectivity of radiation on transfer function of atmosphere is illustrated on fig. 11a, on which dependences of spectral factors of selectivity η are presented as function from transmission τ_n for sources of not selective radiation for various sites of a spectrum with the centers ν (ν – wave number) for optically thin radiator of water vapor. The absorbing medium is atmospheric water vapor. A total pressure P in a selective source and in atmosphere is one atmosphere. The Fig. 11b shows strengthening of display of effect of selectivity with fall of total pressure P to 0,1 atmospheres.

2.3 Functions spectral transmission of vapors H_2O, CO_2 and small components of products of combustion

Let's consider the general empirical technique for calculation of radiating characteristics of a gas phase of products of combustion (Kondratyev & Moskalenko, 1977; Moskalenko et al., 2009), applicable for the decision of problems of radiating heat exchange and the radiation transfer over in torches of aerocarriers, in chambers of combustion of power and power technological units and in the power fire chambers functioning in the conditions of high pressures of a working medium. The developed technique is applicable for function evaluation spectral transmission (the basic radiating characteristic) multicomponent non-uniform on temperature and effective pressure of atmosphere of smoke gases of products of combustion in the chamber of combustion and gas-mains of boilers. A working range of effective pressure $0,01 \leq P_e \leq 100$ atm that provides its use at the decision of problems of radiating heat exchange both in modern boilers, and in perspective workings out of power and power technological units.

Generally at function evaluation spectral transmission $\tau_{\Delta\nu}$ where ν – wave number, Δ – the spectral permission, is necessary to allocate contributions to the absorption caused by wings of remote spectral lines of atmospheric gases $\tau^k{}_{\Delta\nu}$, by the induced pressure absorption $\tau^n{}_{\Delta\nu}$, selective absorption $\tau^c{}_{\Delta\nu}$ by the spectral lines entering into the chosen spectral interval. Then for the set component:

$$\tau_{\Delta\nu} = \tau^k_{\Delta\nu} \times \tau^n_{\Delta\nu} \times \tau^c_{\Delta\nu} . \tag{13}$$

Function:

$$\tau^k_{\Delta\nu} \cdot \tau^n_{\Delta\nu} = \exp\left[-(\beta_{\nu k}(T) + \beta_{\nu n}(T))\omega P\right], \tag{14}$$

where $\beta_{\nu k}(T)$ and $\beta_{\nu n}(T)$ – factors continual and the absorption induced by pressure, depending on temperature T; ω – the component maintenance; P – partial pressure.

For reception of function spectral transmission $\tau^c{}_{\Delta\nu}$ it is offered to use the general parity:

$$\left(\frac{1}{\ln \tau_{\Delta v}}\right)^2 = \left(\frac{1}{\ln \tau'^C_{\Delta v}}\right)^2 + \left(\frac{1}{\ln \tau''^C_{\Delta v}}\right)^2 + \frac{M}{(\ln \tau'^C_{\Delta v})(\ln \tau''^C_{\Delta v})}, \tag{15}$$

where

$$\tau'^C_{\Delta v} = \exp[-k_v(T)\omega] \tag{16}$$

defines function spectral transmission in the conditions of weak absorption and at elevated pressures ($P \geq 10$ atm) in the conditions of the greased rotary structure of a spectrum of absorption,

$$\tau''^C_{\Delta v} = \exp[-\beta_{vc}(T)\omega^{m_v} P_e^{n_v}] \tag{17}$$

- function spectral transmission at small $P_e < 1$ atm in the conditions of strong absorption. The M parameter characterizes change of growth rate of function transmission at transition from area of weak absorption in area of strong absorption. Parameters k_v, m_v, n_v, β_{vc}, are defined from the experimental data received by means of described above measuring complexes. In conformity with the theory of modeling representation of spectra of absorption $k_v = \bar{S}/d$ defines the relation of average intensity to distance between lines, and the size $k_v \Delta v$ - characterizes intensity of group of the spectral lines located in the chosen spectral interval Δv.

It has been shown that the parity (15) describes any modeling structure of a spectrum, including the law of Buger for a continual spectrum of strongly blocked spectral lines. Really, in this case m=1, n=0, β_{vc}=k_v, M = − 1. The overshoot of spectral lines is stronger, the it is more parameter *m* and the less parameter *n* and the closer parameter │M│ to unit. For real spectra parameter M∈{0,-1}. Continual absorption by wings of lines and the absorption induced by pressure is described by a following set of parameters: m=1, n=1, $k_v = \beta_v$, M = − 1.

Let's notice that spectra of the absorption induced by pressure submit to other rules of selection in comparison with vibrational-rotary spectra and the bands of absorption forbidden by rules of selection in vibrational-rotary spectra, become resolved in spectra of the absorption induced by pressure. In this connection the account of the absorption induced by pressure can become necessary in radiating heat exchange in power fire chambers. In power fire chambers the account and continual absorption by wings of strong lines and absorption bands is more important.

With temperature growth the density of spectral lines increases and, hence, parameters m_v, n_v, M_v change. In this connection at calculations $\tau^c_{\Delta v}$ in the conditions of non-uniform on temperature and pressure of medium average values of these parameters in a certain range of temperatures are used.

For calculation $\tau^c_{\Delta v}$ in the conditions of non-uniform on temperature and pressure of medium it is convenient to enter temperature functions:

$$F_{1c}(T) = \frac{K_v(T)}{K_v(T_0)}, \quad F_{2c}(T) = \frac{\beta_{vc}(T)}{\beta_{vc}(T_0)}. \tag{18}$$

Then

$$-\ln \tau^c_{\Delta \nu} = K_{\nu c}(T_0)W_1 \, , \quad -\ln \tau^{"c}_{\Delta \nu} = \beta_\nu(T)W_2^{m_\nu} \, , \tag{19}$$

where

$$W_1 = \int_e \rho(e)F_{1c}[l(T)]dl, \tag{20}$$

$$W_2 = \int_e \rho(e)\left(\frac{P_e(e)}{P_0}\right)^{\frac{n_\nu}{m_\nu}} \frac{1}{F_{2c}^{m_\nu}}[l(T)]dl \, . \tag{21}$$

Here effective pressure:

$$P_e = P_{N_2} + B_{O_2} \cdot P_{O_2} + \sum_{i=1}^{N-1} B_{ik}P_{ik} \, , \tag{22}$$

where P_{N_2} - pressure N_2, P_{O_2} - pressure O_2, B_{ik} – the widening factor (the relation of average semiwidth of lines in the chosen interval of a spectrum for collisions of molecules i-k to average semiwidth of spectral lines in case of impact of molecules of type i with molecules of nitrogen N_2).

Similarly for induced and continual absorption:

$$\beta_{\nu u}(T) = \beta_{\nu u}(T_0)F_u(T) \, , \qquad \beta_{\nu \kappa}(T) = \beta_{\nu \kappa}(T_0)F_\kappa(T) \, . \tag{23}$$

Temperature functions used for calculations $F_u(T), F_\kappa(T), F_{1c}(T), F_{2c}(T)$ can be presented in the tabular form or in the form of simple analytical approximations, for example, in the exponential-sedate form.

It is experimentally shown that for multicomponent atmosphere full function spectral transmission is defined by the law of product of functions on all gas components:

$$\tau_{\Delta \nu} = \prod_i \tau_{i\Delta \nu} \, , \tag{24}$$

where i – component number.

The parity (24) directly follows from static model of spectra and reflects that fact that the thin structure of spectra of each molecule doesn't depend on other molecules. For induced and continual absorption it is a parity it is carried out owing to absence of rotary structure. Numerical modeling of functions spectral transmission on parameters of thin structure of spectra have shown that the parity (24) is carried out with a margin error no more than 1 %.

Parameters K_ν, β_ν, m_ν, n_ν, M are defined from the measured spectra of radiation and radiation absorption by high-temperature gas mediums, modeling with the help heating cells and fiery measuring complexes.

For definition of parameters of functions spectral transmission the data of experimental researches has been added by results of numerical modeling under high-temperature atlases of parameters of the spectral lines prepared with use of the base data, received by means of measuring complexes of the high spectral permission. For an example on fig. 12 spectral

factors of absorption of water vapor K_v, and on fig. 13 – spectral dependences β_v water vapor in bands 1,37, 1,87 and 2,7 μm on experimental data are led. On fig. 14 spectral dependences of factors of absorption CO_2 in band 2,7 μm is given. On fig. 15 spectral factors of absorption K_v in the basic bands CO and NO according to numerical modeling of thin structure of spectra of absorption are illustrated. For vapor H_2O parameters m_v, n_v, M_v poorly depend on length of a wave a range of temperatures 600-2500K and probably to use average values $n=0,45$, $m=0,65$, $M = -0,2$. Strong temperature dependence of spectral factors of absorption in a range of spectrum $10-20$ μm pays attention. At growth of temperature from 300 to 2500K increase intensitys the spectral lines entering into the specified interval of a spectrum, in 6600 times is observed.
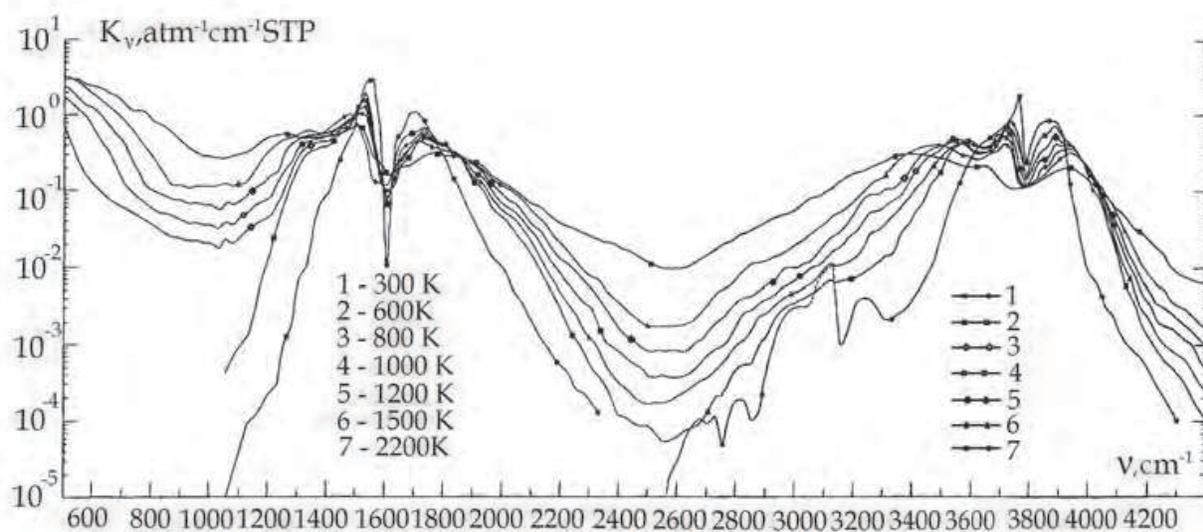

Fig. 12. Spectral factors of absorption K_v water vapor in bands 6,3 and 2,7 μm on experimental data.

Applicability of the received parameterization of functions spectral transmission for the decision of problems of the transfer over of radiation in high-temperature mediums and radiating heat exchange in chambers of combustion with application described above parities for calculations spectral intensitys thermal radiation and nonequilibrium radiation of electronic spectra in non-uniform working mediums under structural characteristics taking into account absorption and scaterring of radiation by a disperse phase has been considered. Main principle of correctness of spent calculations is calculation of equivalent mass on indissoluble trajectories from the radiating volume to a supervision point, including at reflection of radiation from walls and at scattering of radiation by a disperse phase. Streams of thermal radiation on walls of the working chamber are defined by integration spectral intensitys on a spectrum of lengths of waves and a space angle within a hemisphere.

a)

b)

c)
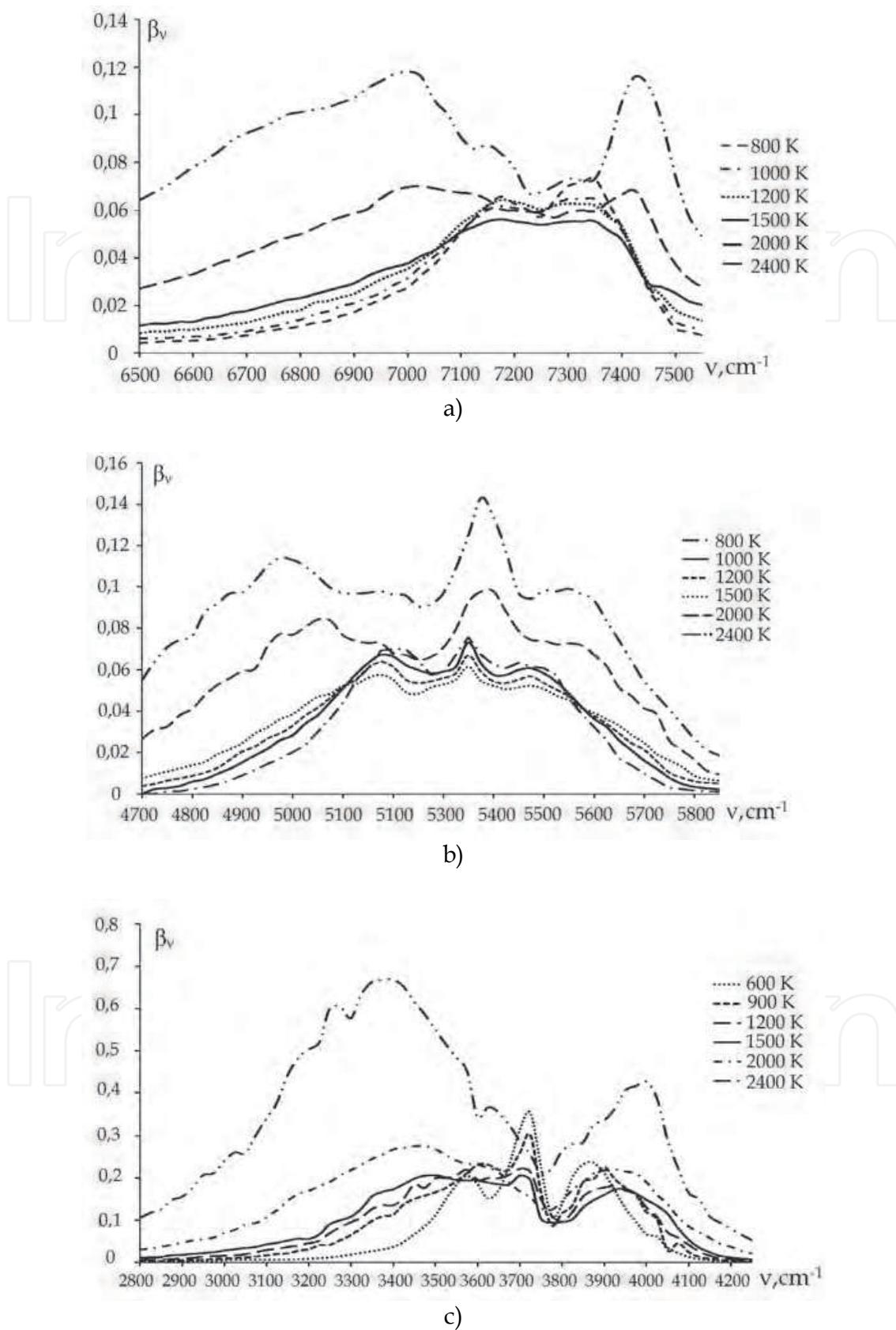
Fig. 13. Spectral dependences of parameter βv in bands 1,37 (a), 1,87 (b) and 2,7 μm (c) water vapor.
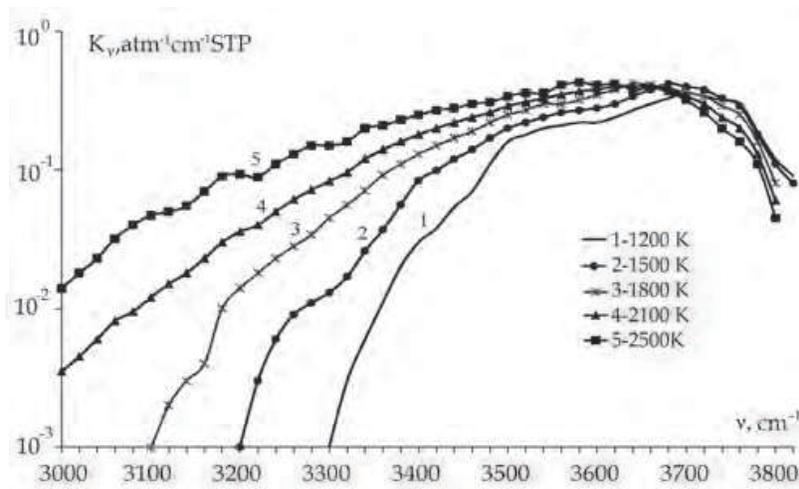
Fig. 14. Spectral dependences of factors of absorption K_v in band 2,7 μm CO_2 on experimental data.
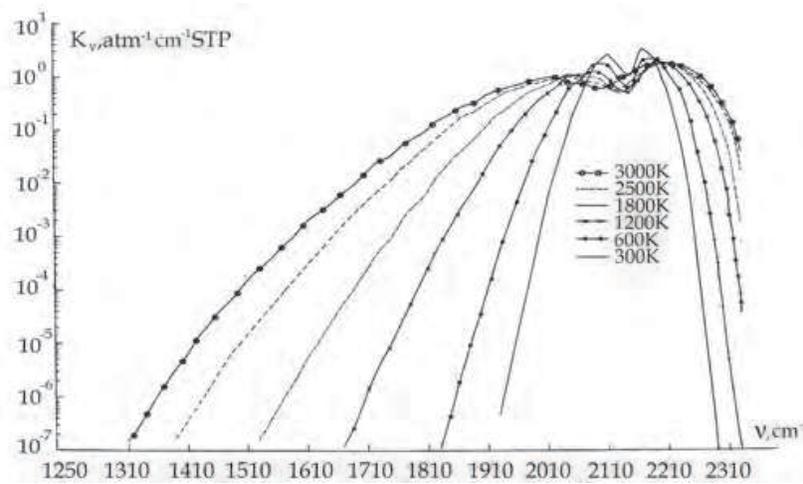
a)
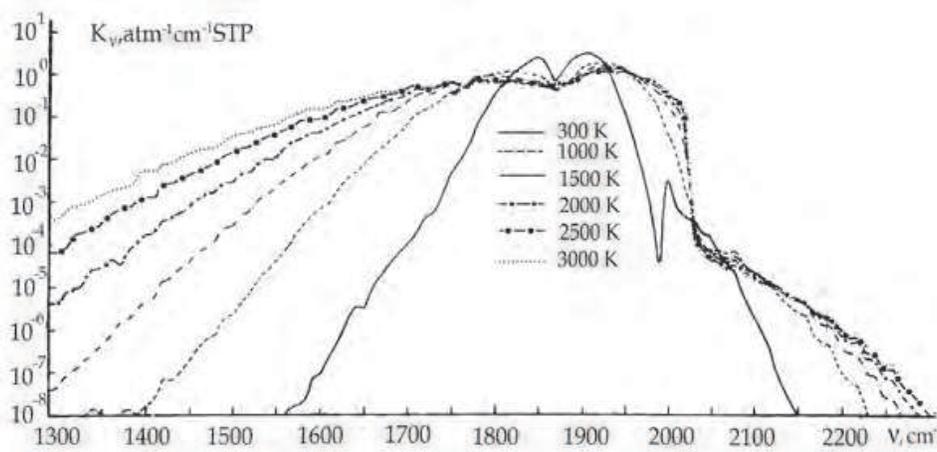
b)

Fig. 15. Spectral dependences of factors of absorption K_v in the basic bands CO (a) and NO (b) by results of numerical modeling of thin structure of a spectrum.

3. Nonequilibrium processes of radiation in flames

Executed spectraradiometry measurements have revealed presence of nonequilibrium radiation in ultra-violet, visible parts of a spectrum as result of display of effect of chemiluminescence in processes of burning of fuel. The contribution of nonequilibrium radiation in radiating cooling a torch has appeared essential. The basic components defining nonequilibrium radiation, are: OH, CH, NO_2, NO, SO_2, CN. Probably also influence of splinters of difficult hydrocarbonic connections which are formed in dissociated process the difficult hydrocarbonic connections which are in wild spirits.

Nonequilibrium radiation is formed by a kernel of a torch and then extends on all volume of the chamber of combustion, being transformed and participating in process of heating of particles of fuel and heatsusceptibility surfaces. Radiating cooling molecules occurs during their relaxation, making $\leq 10^{-4}$ sec, commensurate in due course courses of chemical reaction, and reduces adiabatic temperature of products of combustion in peaks of chemical reactions. Out of zones of chemical reactions radiation is equilibrium.

3.1 Definition nonequilibrium radiating cooling a flame from experimental data

Nonequilibrium radiation is generated by mainly electronic bands of radiation of the raised molecules of products of the combustion, lying in ultra-violet and visible parts of a spectrum and in vibrational-rotary bands. Temperature T of a zone of burning was measured by optical methods with a margin error no more than 2 %. A known chemical composition of gas fuel allows to calculate adiabatic temperature of zones of chemical reactions and to define size $\Delta T = T_a - T$, characterizing radiating cooling zones of active burning. Radiating cooling can be equilibrium and nonequilibrium. Equilibrium radiating cooling ΔT_e it is possible to calculate on absolute spectra of radiation of a flame and on the measured temperature and a chemical composition of products of combustion, speed of the expiration of a stream that allows defining radiating cooling ΔT_n, caused by nonequilibrium radiation.

Nonequilibrium radiating cooling $\Delta T_n = \Delta T - \Delta T_e$ is convenient for characterizing in size $\xi = \Delta T_n / T_a$ that which according to our measurements varies in a range of values (0,02-0,13), and increases with growth of temperature T_a.

Features of registration of average temperature of a flame an optical method have demanded working out of a method of definition ΔT_n in conformity with absolute spectra of the radiation registered by the spectral device, allocated optical systems in volumes of the radiating medium.

For definition nonequilibrium radiating cooling of flames results of measurements by optical methods of temperature hydrogen-oxygen, hydrogen-air, the propane-butane-oxygen, the propane-butane-air, acetylene-oxygen flames, formed by burning of gas fuel of a controllable chemical composition in air or oxygen have been used. Specially developed burning devices provided formation homogeneous for temperature flames in optical measuring channels. The temperature of a homogeneous flame was measured by a method of the self-reference of spectral lines of water vapor and on spectral brightness of radiation of a flame in "black" lines of water vapor or CO_2. Really, for a flame homogeneous for temperature and the gas medium which are in thermodynamic balance, spectral brightness of radiation $B_{\Delta\lambda}$ will be defined by a parity:

$$B_{\Delta\lambda} = B_\lambda^{abb} \left(1 - \tau_{\Delta\lambda}\right), \tag{25}$$

where $\tau_{\Delta v}$ – function of spectral transmission a flame for a small range of length of a wave, B_λ^{abb} – spectral brightness of radiation of absolutely black body on length of a wave λ, Δ - semiwidth of hardware function of a spectrometer. If $\tau_{\Delta v} = 0$ (a black line of radiation), $B_{\Delta\lambda} = B_\lambda^{abb}$ and the size $B_{\Delta\lambda}$ unequivocally defines temperature of a homogeneous flame.

The adiabatic temperature of a flame is calculated on a known chemical composition of products of combustion of burned gas and factors of surplus of oxygen and air α. Comparison of calculated values T_a with the measured optical methods in temperatures of flame T has shown that observable temperature T of a flame always more low T_a. The only thing the reason leading to lower value of size T in comparison with in adiabatic temperature T_a, can be effect radiating cooling a flame.

For the homogeneous radiating medium speed radiating cooling will be defined by the formula:

$$\frac{\partial T}{\partial t} = \frac{\oint_S \left(F^\uparrow(S) - F^\downarrow(S) \right) dS}{\overline{C}p(T)\rho(T)V},$$ (26)

where integration is made on the closed surface S covering all radiating volume V. The size $F^\downarrow(S)$ defines the integrated flux of equilibrium radiation entering into radiating volume V in point S; $F^\uparrow(S)$ represents an integrated flux of the equilibrium radiation leaving radiating volume V in point S; $\overline{C}p(T)$ - a specific thermal capacity of medium at constant pressure:

$$\overline{C}p(T) = \frac{\sum_i C_{pi}(T)P_i(T)}{\sum_i P_i(T)},$$ (27)

where P_i - partial pressure of i-th component. Summation in the ratio (27) is made on all gas components which are a part of products of combustion; $\rho(T)$ - the density of the gas medium, which dimension is defined by dimension $\overline{C}p(T)$,

$$F^\uparrow(S) = \int_0^{\pi/2} \int_0^{2\pi} \int_0^\infty J_\lambda^\uparrow(S,\theta,\phi)\sin\theta\cos\theta d\theta d\phi d\lambda,$$ (28)

$$F^\downarrow(S) = \int_0^{\pi/2} \int_0^{2\pi} \int_0^\infty J_\lambda^\downarrow(S,\theta,\phi)\sin\theta\cos\theta d\theta d\phi d\lambda.$$ (29)

In parities (28), (29) antiaircraft corner θ is counted from a normal to the closed surface in a point of supervision S. Boundary conditions at the decision of the equation of the transfer over were set in conformity with the constructional decision of measuring complexes (Moskalenko et al., 1992). Functions spectral transmission were calculated with use of a two-parametrical method of equivalent mass on indissoluble optical ways from the radiating volume to a supervision point (Kondratyev & Moskalenko, 2006).

At data processing of measurements were considered flames horizontal development of two counter streams of the flame surrounded with the quartz heat exchanger, reducing radiating

cooling a flame and promoting preservation of uniformity of temperature within an optical way of thermal radiation to the optoelectronic device, and also excluding formation sooty ashes as a result of process of pyrolysis of combustion products at burning hydrocarbonic fuels. The geometrical way of each of counter streams of a flame made 20 cm at speed of a current of a stream ω =8-10 m/s. The geometrical way to devices with vertical development of a flame made 6 cm at speeds of a current ω =10-15 m/s. Researchers have shown that in devices with water cooling of the case of the chamber of combustion (Moskalenko et al., 1992) at burning of hydrocarbonic fuel it is formed sooty ashes. Therefore in these devices as fuel the pure hydrogen excluding possibility of formation sooty ashes in products of combustion was used.

On fig. 16 and in table 2 results of definition of size $\xi = \Delta T_n / T_a$ for hydrogen-oxygen, hydrogen-air, the propane-butane-oxygen, the propane-butane-air, acetylene-oxygen flames are shown. With increase adiabatic temperatures T_a the size ξ increases and in a range of temperatures T_a from 1800 to 3200K varies from 2 % to 13 %.
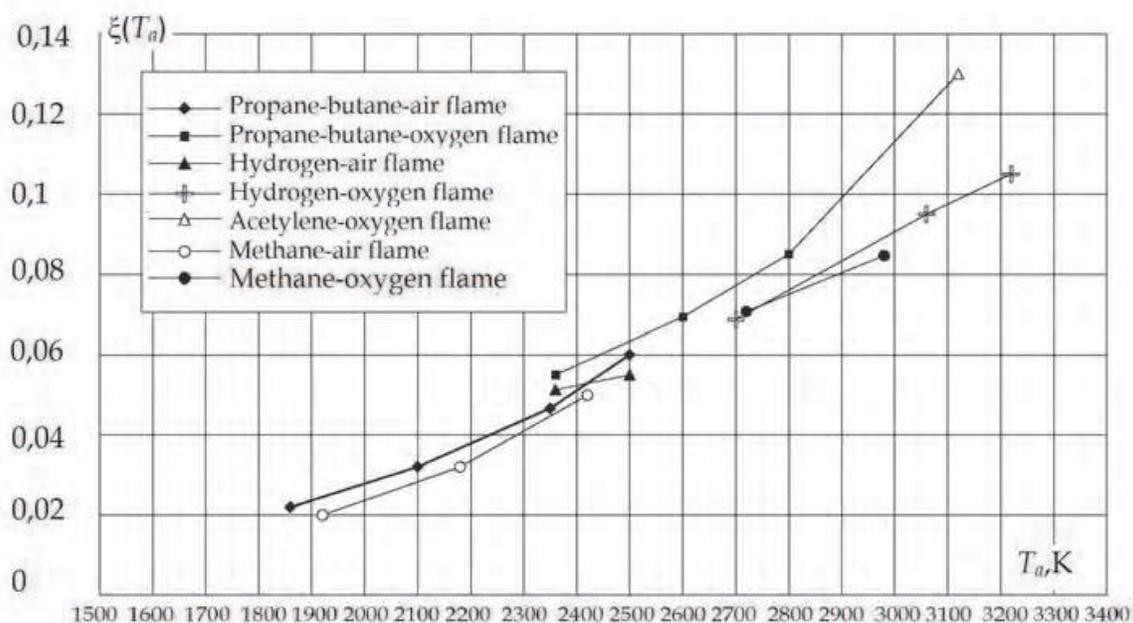

Fig. 16. Dependence of parameter $\xi = \Delta Tn/Ta$ from adiabatic temperatures Ta.

As have shown results of experimental definition of function of source B_λ and factors of nonequilibrium $\eta_\lambda = B_\lambda(T) / B_\lambda^{abb}(T)$, where $B_\lambda^{abb}(T)$ is spectral brightness of absolutely black body (Planck's function), nonequilibrium radiation is formed mainly in electronic spectra of radiation of the molecules located in ultra-violet and visible parts of a spectrum. The effect nonequilibrium radiations in the vibrational-rotary bands lying in infra-red area of a spectrum, is shown considerably only at adiabatic temperature T_a> 2500 K.

The obtained data of experimental researches concerns optically thin torch when influence nonequilibrium is shown in a greater degree. Therefore the data presented on fig. 16 and in tab. 2, can be used for an estimation of the maximum size of energy which is transferred on heatsusceptibility to a surface in case of burning of gaseous fuel. It can be estimated on radiation of gas products of combustion of a kernel of a torch and on change enthalpy of

combustion products. In the first case we will use the law of Stefan-Boltzman's defining an integrated hemispherical stream of radiation of absolutely black body,

$$F(T) = \sigma T^4 .$$ (30)

T_a , K	$\xi = \Delta T_n / T_a$	Type of flame
1860	0,021	propane-butane-air
2100	0,032	propane-butane-air
2350	0,048	propane-butane-air
2500	0,06	propane-butane-air
2360	0,055	propane-butane-oxygen
2600	0,069	propane-butane-oxygen
2800	0,085	propane-butane-oxygen
3120	0,13	acetylene-oxygen
2360	0,051	hydrogen-air
2500	0,056	hydrogen-air
2700	0,068	hydrogen-oxygen
3060	0,095	hydrogen-oxygen
3220	0,105	hydrogen-oxygen
1920	0,020	methane-air
2180	0,033	methane-air
2420	0,050	methane-air
2720	0,071	methane-oxygen
2980	0,094	methane-oxygen

Table 2. Influence of nonequilibrium processes of radiation on radiating cooling a flame. T_a is adiabatic settlement temperature; ΔT_n is radiating cooling the homogeneous flame, caused by nonequilibrium radiation. Factor of surplus of air and oxygen α> 1.

Let's enter integrated function transmission:

$$\tau(T) = \int\limits_0^\infty B_\lambda(T)\tau_\lambda(T)d\lambda \Big/ \int\limits_0^\infty B_\lambda(T)d\lambda .$$ (31)

As the range of changes of temperature $(T_a\text{-}T)$ is insignificant, in the specified range of temperatures of a flame $\in \{T_a - T\}$ we will accept τ_n=const. Then a parity:

$$\frac{\Delta F}{F(T_a)} = \frac{F(T_a) - F(T)}{F(T_a)} = 1 - \frac{F(T)}{F(T_a)} = 1 - \frac{F(T_a - \Delta T_n)}{F(T_a)} =$$

$$= 1 - \frac{\sigma(T_a - \Delta T_n)^4}{\sigma T_a^4} = 1 - \left[1 - \left(\frac{\Delta T_n}{T_a}\right)^4\right] \approx \frac{4\Delta T_n}{T_a} .$$ (32)

Thus, in a case optically a thin torch on heatsusceptibility surfaces without easing can get from 8 % to 30 % of full radiation of a torch.

Change enthalpy of combustion products will be defined by the formula:

$$\Delta H = \sum_i \left(\int_T^{T_a} C_{pi}(T) \, dT \right) V_i \, , \tag{33}$$

where $C_{pi}(T)$ - a specific thermal capacity at constant pressure for a component i combustion products, V_i - led to standard temperature and pressure volumes of components of products of combustion (P_{0i}=1 atm, T_{0i}=273K). Summation is carried out on all components i combustion products.

Volumes V_i are calculated on a known chemical composition of gas fuel and value of factors of surplus of air or oxygen. Size estimations $\Delta H / H_a$ yields the results close to sizes $\Delta F / F$ (T_a).

In case of mediums with the big optical density effects of influence nonequilibrium radiations are extinguished owing to suppression processes of chemiluminescence, caused by absorption of nonequilibrium radiation and display radiationless transitions in molecules. Because nonequilibrium radiation is formed in ultra-violet and visible parts of a spectrum, and also in infra-red area of a spectrum, in the transfer over of nonequilibrium radiation it is important to consider radiation absorption thing-dispersion ashy fraction and the hydrocarbonic connections absorbing radiation in spectral area of generation of nonequilibrium radiation. At absorption of nonequilibrium radiation there is a heating of particles of fuel and their ignition, and absorption of nonequilibrium radiation by heatsusceptibility surfaces weakens.

3.2 Definition of spectral factors of nonequilibrium vibrational temperature of components in flames

Quantum-mechanical consideration of a problem of formation of spectra of radiation of flames shows that presence nonequilibrium in radiation in electronic spectra (Moskalenko et al., 2009) it is accompanied by the nonequilibrium mechanism of radiation and in vibrational-rotary spectra as cores, overtone and composition bands, as have confirmed results of our measurements. The mathematical model of the transfer over of radiation is developed for the analysis of spectra of radiation flames in nonequilibrium radiating biphasic mediums in approach of unitary scattering of radiation (Moskalenko et al., 2009; Moskalenko & Loktev, 2009). The Chemical composition of products of combustion was calculated (Alemasov et al., 1973). Measurements were carried out on the spectral installations described in section 2.1 in spectral area 0,2÷25 μm in a range of temperatures 1500-2900 K. Hydrogen, methane, the propane-butane and acetylene in oxygen and in air were burned. The spectral resolution made Δ=3÷5 cm-1. Besides, in the field of a spectrum 2,5÷3,5 μm were used results of the measurements executed with the high spectral resolution Δ=0,05 cm-1 by means of the Fourier spectrometer that has allowed to reveal influence nonequilibrium a flame in the basic band OH 2,8 μm. Results of the executed researches have shown that radiation of water vapor in vibrational-rotary bands is equilibrium. Nonequilibrium character of radiation CO_2 starts to be shown at thermodynamic temperatures of flame T_t>2100 K. Nonequilibrium character of radiation in electronic spectra of oxides of nitrogen in a spectral range 0,3÷0,7 μm was detected. Diffused radiation NO_2 has poorly expressed maximum of radiation in a spectrum range 0,55÷0,58 μm. At burning CH_4, propane-butane, C_2H_2 there is a formation of particles of soot to optical

density on length of a wave $\lambda=0{,}55\mu m$ accordingly equal 0,098; 0,2; 0,4 m^{-1} in a flame. Spectral dependences of factors of absorption and easing sooty ashes are used by us for restoration of its microstructure with the subsequent calculation of matrixes light scattering on a radiation spectrum (Moskalenko et al., 2010). We will more low stop on the analysis of spectra of nonequilibrium radiation of hydroxyl OH.

For research of radiating characteristics of a hydroxyl it is expedient to use hydrogen-oxygen a flame in order to avoid overlapping of bands of radiation OH other radiating components. Also it is expedient to choose modes of burning with factors of surplus of an oxidizer $\alpha_{ox}<1$. Spectra of radiation H_2-O_2-flame are measured on installation SUVGI (Moskalenko et al., 1980; Moskalenko et al., 1992) and laboratory breadboard models of this installation at temperatures 1500-2500K. Hydrogen-oxygen flames, used in the present researches, have is bluish-white coloring with less contrast external zone of orange color. The flame height strongly depends on a mode of burning and on the average makes 30 cm. At heights more than 25 mm over hydrogen and oxygen capillaries ardent streams see height more merge, forming a continuous radiating torch. The maximum concentration of the basic radiating components of the hydrogen-oxygen flame: water vapor and a hydroxyl makes accordingly 58,46 % (at $\alpha_{ox}=1$) and 12,21 % (at $\alpha_{ox}=1{,}3\div1{,}5$). Thermodynamic parameters of products of combustion of the hydrogen-oxygen flame, calculated at pressure P=1atm, are presented in table 3. In spectra of radiation of a flame the most intensive bands are observed in a range $261\div360$ nm. In flames with $\alpha_{ox}<0{,}5$ in combustion products molecular oxygen is absent and in spectra of radiation of a band of Schuman-Runge of hot molecular oxygen weren't observed.

Unlike a propanee-butane-oxygen flame, a hydrogen-oxygen flame is transparent, since its emissivity in the visible is $\varepsilon_\lambda \leq 0.003$. Weak emission bands belonging to water vapor are observed in the neighborhoods of $\lambda = 577.5, 579.7, 693, 718, 766$, and 813 nm. The Na doublet was also detected from the slight concentration of sodium in the hydrogen. The emission peak of nitrogen dioxide (NO_2) is observed in the range of 550–580 nm. Members of the Delandres scheme of the ground state of the OH bands make a small contribution to the visible emission from the hydrogen-oxygen flames.

Table 3 lists the main thermodynamic parameters of the combustion products of the hydrogen-oxygen flame, including the thermodynamic temperature T of the flame and the chemical composition of the combustion products in the form of the volume concentrations of the components, as functions of the oxygen excess coefficient α_{ox}.

The OH radical is formed in all combustion processes for hydrogen-containing fuels and plays a significant role in the chemical chain reaction mechanism (Kondratyev, 1958; Kondratyev & Nikitin, 1981). It is a component of the combustion products in the exhaust plumes of ballistic rockets. Intense UV emission of the OH group is an important signifier of the launching of rockets and the firing of artillery systems. Large amounts of the OH groups are produced during nuclear explosions in the atmosphere.

The emission and absorption spectra of OH in hydrogen-oxygen flames has been studied for several decades. Small sized premixed flames have been used for this. The results indicate a disequilibrium over the internal degrees of freedom in the reaction zone of the flame. The emission from hydrogen flames at low pressures is essentially pure chemiluminescence. The most important criterion for chemiluminescent radiation is that the absolute intensity of the OH group radiation must exceed its equilibrium value because of a nonequilibrium vibrational and rotational energy distribution which leads to anomalously high vibrational

and rotational temperatures. Increasing the pressure and introducing inert gases into the combustion zone cause quenching of the chemiluminescence on the part of hydroxyl groups. At low pressures the emission intensity of the OH groups in hydrogen low-temperature flames is many orders of magnitude greater than the equilibrium emission intensity. Here we measure the UV emission and absorption of OH in a hydrogen-oxygen flame. This flame can be used to model the temperatures in the exhaust plumes of rocket engines.

α_{ox}	T, K	K_1	H_2	H_2O	H	OH	O	O_2
0,1	1089	0,79	0,9	0,1	-	-	-	-
0,15	1442	1,19	0,85	0,15	-	-	-	-
0,2	1763	1,59	0,7998	0,2	0,002	-	-	-
0,25	2047	1,98	0,7483	0,2497	0,0019	-	-	-
0,3	2272	2,38	0,6917	0,2977	0,0099	0,0006	-	-
0,35	2475	2,78	0,6354	0,3444	0,0181	0,0019	-	-
0,4	2620	3,18	0,5756	0,3871	0,0379	0,0051	0,0001	-
0,45	2733	3,57	0,5166	0,4256	0,0468	0,0102	0,0005	0,0001
0,5	2822	3,97	0,4604	0,4595	0,0606	0,0174	0,0014	0,0005
0,6	2945	4,76	0,3617	0,5129	0,0809	0,0368	0,0049	0,0027
0,7	3017	5,56	0,2842	0,5483	0,0896	0,0584	0,011	0,0083
0,8	3055	6,35	0,2256	0,5694	0,0895	0,0784	0,0186	0,0183
0,9	3071	7,14	0,1818	0,5804	0,0843	0,0946	0,0261	0,0326
1,0	3074	7,94	0,1486	0,5846	0,0768	0,1065	0,0328	0,0504
1,1	3068	8,73	0,1231	0,5843	0,0688	0,1146	0,0382	0,0708
1,2	3057	9,52	0,1031	0,5809	0,0609	0,1196	0,0422	0,0931
1,3	3043	10,32	0,0871	0,5755	0,0536	0,1221	0,045	0,1164
1,5	3008	11,91	0,0636	0,5609	0,0413	0,1221	0,0476	0,1643
2	2907	15,87	0,0317	0,5171	0,0212	0,107	0,0435	0,2792
3	2699	23,81	0,0093	0,4357	0,0055	0,0664	0,0245	0,4582
5	2291	39,69	0,0007	0,3215	0,0002	0,0172	0,0038	0,6563
10	1546	79,37	-	0,1817	-	0,0002	-	0,8181

Table 3. Thermodynamic parameters of the combustion products of hydrogen-oxygen flames at a pressure of *P*=1atm.

The UV spectrum of the OH is formed by the electronic transition $A^2\Sigma - X^2\Pi$ consisting of the four most intense sequences Δv = 0, ±1, ±2 lying in the region 261–360 nm. The 0–0 band is the most intense. The nonequilibrium OH emission of the flame is characterized by the spectral nonequilibrium coefficient of the radiation defined η_λ as the ratio of the intensity of the nonequilibrium emission to the equilibrium intensity at wavelength λ. The spectral brightness of the equilibrium OH emission $B_{\lambda e}^{OH}$, for a uniform medium is given by:

$$B_{\lambda e}^{OH} = B_{\lambda}^{0}\left(1 - \tau_{\lambda}^{OH}\right),$$ (34)

where $\tau_\lambda{}^{OH}$ is the spectral transmission function of the OH groups in the flame; $B_{\lambda e}^{OH}$ is the absolute spectral brightness of the OH emission expressed in energy units, and is the spectral brightness of an absolute black body at the thermodynamic temperature of the flame.

In accordance with the definition, the spectral nonequilibrium coefficient is written in the form:

$$\eta_\lambda = B_{\lambda n}^{OH} \big/ B_{\lambda e}^{OH} = B_{\lambda n}^{OH} \bigg/ B_{\lambda e}^{0}\left(1 - \tau_\lambda^{OH}\right), \tag{35}$$

Where $B_{\lambda n}^{OH}$ is the spectral brightness of the nonequilibrium emission from the OH groups.

An examination of the theory of nonequilibrium radiation transfer (Moskalenko et al., 2006) shows that, under the given conditions for formation of the flare, η_λ depends on the optical thickness of the emitting medium and reaches a maximum for small optical thicknesses of OH, when the spectral transmission function $\tau_\lambda{}^{OH} \to 1$. If η_λ is obtained at $\tau_\lambda{}^{OH}$, then $\eta_{\lambda\,max}^{OH} = \eta_\lambda^{OH} \big/ \tau_\lambda^{OH}$.

The quantity $\eta_{\lambda max}$ shows up in the computational integro-differential equations for modelling radiative transfer in nonequilibrium radiating media (Moskalenko & Zaripov, 2008). Studies of the integral effects of nonequilibrium radiative processes on radiative transfer have shown that the effect of the nonequilibrium in the radiative processes increases with the adiabatic temperature T_a of the flame; this is also confirmed by the present spectral measurements of the nonequilibrium OH emission. The values of $\eta_{\lambda max}$ can be used for determining the spectra (wavelength dependence) of the vibrational temperatures (Moskalenko et al., 2010).

In the faint nonequilibrium emission bands, the spectral transmission $\tau_\lambda \to 1$ and small values of $(1 - \tau_\lambda)$ cannot be observed experimentally. In that case, the vibrational temperatures obtained for the fainter bands can be used to find the spectral absorption coefficients and integral intensities of the faint emission bands whose absolute emission spectra have been recorded by measurement devices.

In order to determine the degree of nonequilibrium of the OH group emission, their transmission spectra were measured under the same conditions as those for measuring the emission spectra. The structure of the transmission spectra correlates with the structure of the emission spectra. The resulting spectral variations in η_λ and $\eta_{\lambda max}$ (fig. 17) are rapidly varying. The degree of variation in the 281–296 nm range is slightly higher than in the 306–328 nm range. The maximum value of $\eta_{\lambda max}$ for T=2380 K is 100. In the 306–328 nm band, $\eta_{\lambda max}$ reaches 50 (fig. 17).

It should be noted that the spectral dependences of η_λ for different temperatures are essentially different. From our standpoint, the reason for this is that it is impossible to make the conditions for obtaining the emission and transmission spectra completely identical, since they have were not recorded simultaneously. The existence of a spectral variation in $\eta_{\lambda max}$ indicates that the vibrational temperature may depend on the vibrational and rotational quantum numbers. In addition, the shape of the spectrum lines may have an effect on the value of η_λ. Turbulent inhomogeneity during burning of the flame may also have some effect on η_λ. For practical calculations it is appropriate to introduce the average

degree of nonequilibricity $\bar{\eta}_{\lambda \max}$ which for, say, the sequence is $\bar{\eta}_{\lambda \max}(\Delta \upsilon = 0) = 18$, and for the sequence $\Delta \upsilon = +1$, is $\bar{\eta}_{\lambda \max}(\Delta \upsilon = +1) = 28$ at T=2380 K. According to the theory of formation of nonequilibrium emission process $\bar{\eta}_{\lambda \max}(\Delta \upsilon = -1) = 28$ for the sequence $\Delta \upsilon = -1$. This value of $\bar{\eta}_{\lambda \max}$ and the absolute spectral intensities of the nonequilibrium emission from the hydroxyl group have been used to determine the spectral absorption coefficients and the integrated absorption intensity of the OH for the $\Delta \upsilon = -1$ sequence (Fig.18).
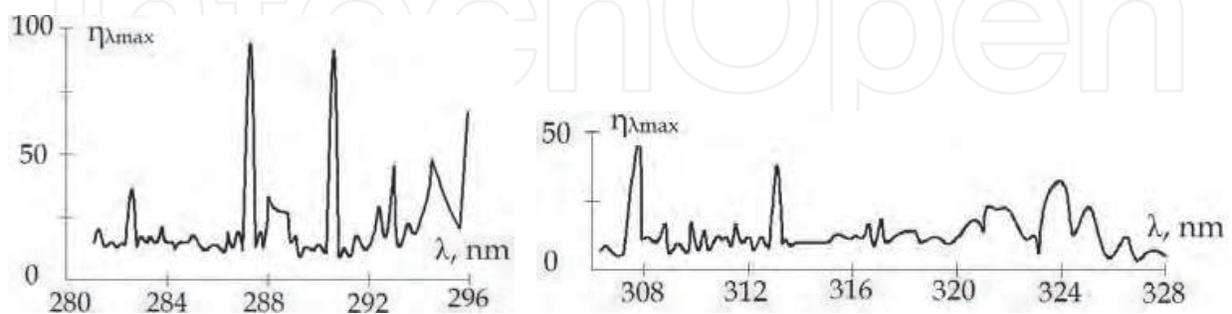

Fig. 17. Spectral dependence of the maximum degree of nonequilibrium in the emission from OH groups at a temperature of 2380 K.
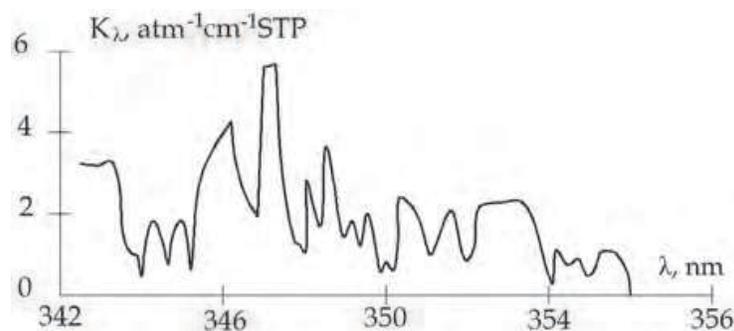

Fig. 18. Spectral dependence of the absorption coefficient for the emission from OH groups in the 342–356 nm range at 2380 K obtained from spectra of the nonequilibrium flame emission.

Our measurements of the absolute intensity spectrum can be used to determine the OH vibrational temperature by the method of (Broida and Shuler, 1952) using the formula:

$$0,624 \cdot \frac{E_1 - E_2}{T} = 4 \cdot \lg \frac{\lambda_2}{\lambda_1} + \lg \frac{P_1}{P_2} + \lg \frac{J_2}{J_1} , \qquad (37)$$

where E_1 and E_2 are the energies of the upper vibrational levels of the chosen emission sequences; λ_1 and λ_2 are the
locations of the centers of the bands or of their edges; P_1 and P_2 are the vibrational transition probabilities; J_2 and J_1
are the emission intensities of the individual vibrational bands of the chosen sequences.
The values of J_2 and J_1 are determined experimentally after energy calibration of the emission spectra. The position of the edges of the bands can be determined fairly accurately after spectral calibration of the measured emission spectra. The vibrational transition

probabilities P_1 and P_2 differ considerably according to the data of various authors. Thus, it has been proposed (Moskalenko and Loktev, 2009) that the vibrational temperatures be measured from $\eta_{\lambda \max}$, and the average vibrational temperature, from $\bar{\eta}_{\lambda \max}$. It should be noted that the integrated intensities of the electronic absorption spectra for the $\Delta \upsilon = 0, \pm 1$ sequences can be used in an experimental determination of the transition probabilities P for these sequences. When Eq.(37) is used legitimately, the vibrational temperatures found by the two different methods (Broida & Shuler, 1952; Moskalenko & Loktev, 2009) should coincide.

The results of this determination of the vibrational temperatures indicate a nonequilibrium distribution of the energy released during the combustion reaction over the vibrational levels of the electronically excited state $A^2 \Sigma^+$. The integrated intensities of the OH group bands for the sequences $\Delta v = 0, +1, -1$ are equal, respectively, to 30592, 14472, and 1980 atm^{-1}·cm^{-2} at STP. According to the present measurements, the total intensity of all the absorption bands of the OH groups in the 281–333 nm range is 47044 atm^{-1}·cm^{-2} at STP. The intensities are in the proportion $S(\Delta v = 0) : S(\Delta v = +1) : S(\Delta v = -1) = 1:0.49:0.065$.

Figure 19 shows the measured spectral dependence of the absorption coefficients of the hydroxyl groups and Fig. 20 the spectral dependence of the vibrational temperature $T_{\lambda k}$ for the $\Delta v = 0, +1$ sequences of the hydroxyl bands according to the formula (Moskalenko & Loktev, 2009):

$$T_{\lambda k} = \frac{C_2}{\lambda} \left\{ \ln \left[\frac{\exp(C_2 / \lambda T) - 1}{\eta_{\lambda \max}} + 1 \right] \right\}^{-1} , \tag{38}$$

where λ is the wavelength, T is the flame temperature, and C_2 is the second constant in the spectral brightness of a black body (Planck function).
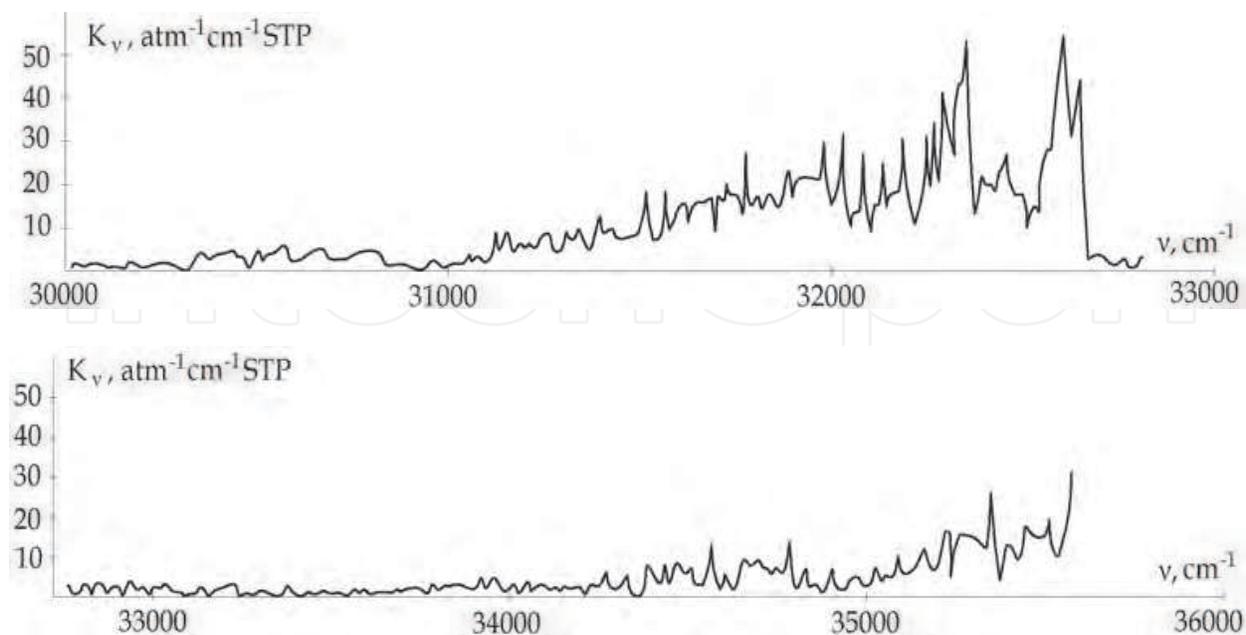

Fig. 19. Spectral dependence of the absorption coefficient Kv for OH groups at 2450 K in the 281–333 nm range (30000–36000 cm^{-1}).

The data obtained here can be used to study the mechanisms responsible for the nonequilibrium character of the emission from hydrogen-oxygen flames, calculating the spectral brightness of the UV emission from rocket exhaust plumes, solving radiative heat transfer problems in power generation furnaces, and in atmospheric nuclear explosions. The present study of the effect of nonequilibrium processes on the formation of the emission spectra of hydrogen-oxygen flames applies to a total pressure of $P = 1 \cdot 10^5$ Pa (1 atm) in the flames. The radiative nonequilibrium coefficients are higher at lower flame pressures, as confirmed by experiments on the effect of nonequilibrium radiative processes on radiative cooling of flames (Moskalenko and Zaripov, 2008). These data show that nonequilibrium radiative processes must also have an effect on the vibrational-rotational emission bands of OH, and the degree of this influence will depend on the relaxation time of hydroxyl from an excited electronic state into an equilibrium state and will show up in the form of additional bands that are shifted toward the IR relative to the main transition. Because of overlap of the main vibrational-rotational band of OH with the intense emission spectrum of water vapor, it will be necessary to measure the emission spectra of flames with high spectral resolution in order to establish the effect of nonequilibrium processes on the formation of the IR emission spectrum of OH. However, the present analysis of the emissivity spectra of hydrogen-oxygen flames has revealed the existence of continuum absorption in the 4.1–4.4 μm range owing to vibrational-rotational transitions of OH groups in excited electronic states (See Fig. 21).
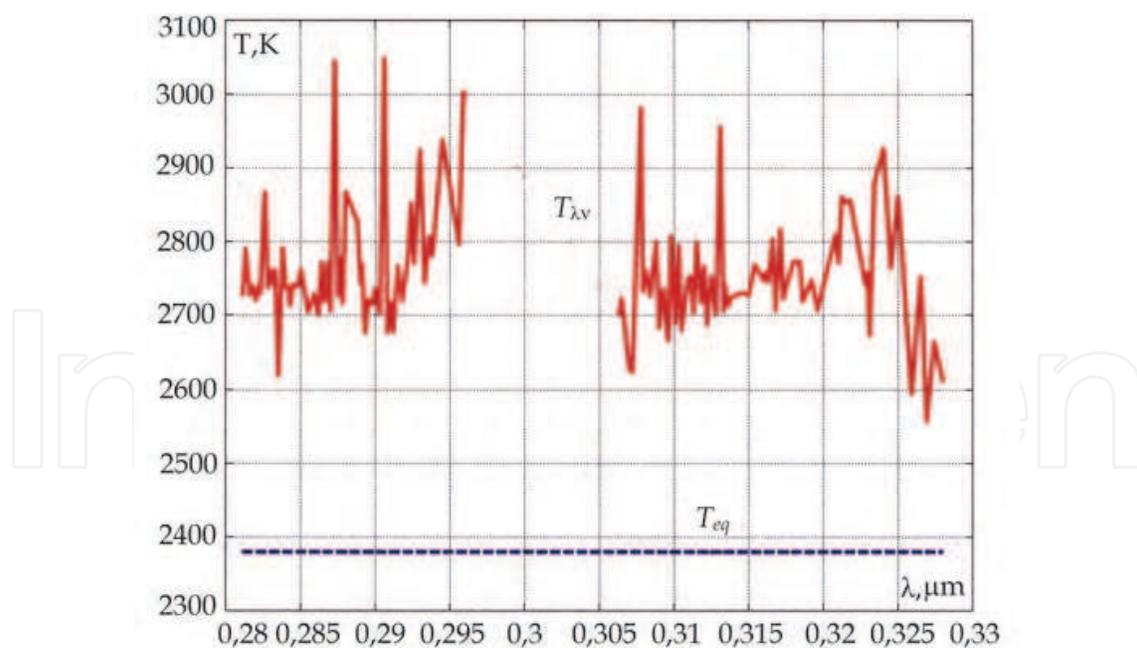

Fig. 20. Spectral dependence of the equilibrium thermodynamic temperature T_{eq} and the vibrational temperature $T_{\lambda v}$ for the $\Delta v = 0, +1$ sequences of the electronic bands of the hydroxyl group.
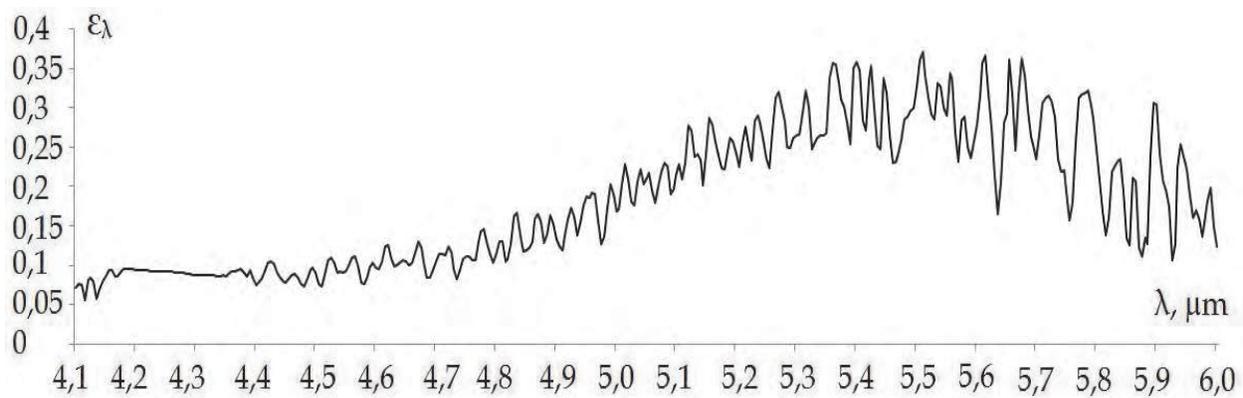
Fig. 21. Spectral emissivity of a hydrogen-oxygen flame with continuum emission of the hydroxyl group in an excited electronic state in the 4.1–4.4 μm range.

The analysis of spectra of radiation of the high spectral permission the hydrogen-oxygen flame in a spectral range of 3000-3500 cm^{-1} received at the spectral permission $\Delta = 0,1$ cm^{-1} (Moskalenko et al., 1992), has revealed presence of nonequilibriumnes in the basic band v_1 hydroxyls OH. In a considered range of a spectrum radiation is formed by vibrational-rotary bands of vapor H_2O and hydroxyl OH. The spectrum of radiation of a flame was energetically not normalized. Besides, because of presence in experimental installation not blown and anonvacuum a site of an optical way the true spectrum of radiation of a flame is transformed by lines cold (T=291 K) water vapor and carbonic gas. For definition of vibrational temperature of hydroxyl OH the true spectrum of radiation corrected from influence of hardware distortion and atmospheric absorption of radiation by vapor H_2O and CO_2 at first is restored. Are most informative for definition of vibrational temperature of a Q-branch of band OH which vibrational temperature surpasses equilibrium temperature of a flame in a spectrum of wave number (vibrational temperature of vapor H_2O in a flame) on size ΔT_v=350÷850 K at average size ΔT_v=650K. This value ΔT_v is recommended to be used at definition of the contribution of radiation OH in radiating heat exchange in high-temperature mediums, including chambers of combustion of boiler installations. We will notice that nonequilibrium spectra of radiation OH in the basic vibrational-rotary band 0 – 1 it is caused by formation as a result of chemical reactions of molecules OH in the basic electronic state with superfluous population of the raised vibrational levels in comparison with equilibrium and transitions of molecules OH with the nonequilibrium populated raised electronic state to selection rules on vibrational and rotary quantum numbers. Definition of vibrational temperature from spectra of radiation is more preferable, as nonequilibrium radiation amplifies not only at the expense of increase in intensity of lines with growth of vibrational temperature ΔT_k, but also growth of function of source $B_\lambda (T_v)$ with increase T_v.

In spectra of radiation of a flame influence nonequilibrium radiations OH in vibrational-rotary bands of the first and second overtones of the basic and raised electronic states is revealed. Their influence on radiating heat exchange high-temperature of flames can be more essential in connection with growth integrated intensitys bands $2v_1$, $3v_1$ OH with increase in temperature and weaker overshoot of spectra OH lines of water vapor. Bands $2v_1$ and $3v_1$ OH the raised electronic state settle down in a vicinity of lengths of waves 2,1 and 1,4 μm, and for the basic electronic state they are in a vicinity of lengths of waves 1,43 and 1 μm.

4. Results of definition of a microstructure of sooty ashes and its optical characteristics

Sooty ashes it is generated at burning of any hydrocarbonic fuel, including wood and an industrial production waste. The nobility suffices for the decision of the scalar equations of the transfer over of radiation spectral factors of absorption, scattering and indicatryss of scattering ashes and their spatial distribution on the radiating volume. The last depends on a chemical composition and a microstructure sooty ashes which are defined by a kind of fuel and a mode of its burning. The least concentration sooty ashes are observed at fuel burning in oxygen with surplus factor α≥ 1 and at most high temperatures of a flame (Moskalenko et al., 2010). Also more thin microstructure ashes in this case takes place. At burning firm power fuel in fire chambers of boiler installations and power technological units the microstructure ashes in top internal volume changes in process of combustion of particles and is multimodal in connection with simultaneous generation sooty ashes in the course of fuel combustion. Thus a roughly-dispersion the fraction ashes is defined by characteristics of grinding devices. For gaseous fuel optical characteristics strongly depend on fuel structure. At hydrogen burning sooty ashes this kind of fuel isn't formed also is non-polluting at its burning in oxygen atmosphere. At burning of gas hydrocarbonic fuel a microstructure sooty ashes and its mass concentration in a flame depends on structure of gas fuel and can change largely (Moskalenko et al., 2010).

4.1 Results of definition of a microstructure of sooty ashes at burning of gas fuel
Variety used fuels and technologies of their burning studying of influence of a chemical composition of fuel, a microstructure of its scattering, a way of giving of fuel and an oxidizer (air), a fire chamber design, burning cause of devices on radiating heat exchange. Last is defined by a chemical composition, a microstructure and a phase condition of hot particles of fuel, a chemical composition of a gas phase of products of combustion and radiating characteristics ashes which is generated in the course of burning of fuel or as a result of ionic nucleation from a gas phase of products of combustion. Process of burning of fuel is accompanied by simultaneous radiating heat exchange and mass exchange combustion products on volume of a fire chamber and a heat transfer to evaporating surfaces. In the present work possibilities of definition of microstructural characteristics of ashes from data on easing of radiation by products of combustion and from radiation optical characteristics of flames which are included into the decision of the scalar equation of the transfer over of radiation are considered and are necessary for modeling of radiating heat exchange in high-temperature diphasic mediums, for example, in chamber fire chambers of power and power technological units. Thereupon optical characteristics industrial ashes are analysed, including sooty particles of the most probable not spherical forms. In case of spherical and cylindrical particles calculations were carried out under the theory of Mi. In case of not spherical particles optical characteristics were calculated in approach of geometrical optics and effective sections of absorption of scattering and scattering indicatryss are received by their averaging on space within a space angle 4π in the assumption that spatial orientation depending on a radiation direction is equiprobable. This assumption is proved enough in case of the decision of problems of radiating heat exchange in combustion chambers where strong turbulence of products of combustion and presence of whirlwinds is observed. For the analysis results of measurements of spectra of radiation of radiation and radiation easing flames, received on measuring complexes (Moskalenko et al., 1980, 1992) and their breadboard models.

Microstructure restoration ashes from the given spectral measurements of radiation of radiation of a flame and easing of radiation by a flame is a return task of remote sounding and demands for the decision of data on spectral dependences of optical characteristics ashes from distribution of particles in the sizes. Ashe of combustion products is polydisperse and on the modeling chosen by us it is represented superposition of separate fractions, microstructure N (r) which is defined by parity (Kondratyev & Moskalenko, 1983):

$$N(r) = \sum_{i=1}^{N} N_i(r) = \sum_{i=1}^{N} A_i \cdot r_a^{a_i} \cdot \exp\left[-b \cdot r^{c_i}\right], \tag{39}$$

where A_i, a_i, b_i, c_i – parameters of i-th fraction, N – number of fractions. As well as in (Kondratyev & Moskalenko, 1983) decisions on the restored spectral factors of easing and radiation absorption ashes we will represent from them normalized for length of a wave λ =0.55 μm, and the mass maintenance ashes on an optical way we will express in an optical thickness $|-\ln\tau|$, where τ – function spectral transmission on length of a wave λ =0.55 μm. The essence of a problem of restoration of a microstructure ashes consists in definition of weight functions $N_i(r)$ which in the best way will describe spectral dependence of the measured factors of absorption and radiation easing ashes (see fig. 22).

It is necessary to notice that flames form strongly absorbing gas medium so lengths of waves for the decision of a return task should be chosen so that radiation of gases in them was minimum. Inclusion in processing of lengths of waves with $\lambda > 4.2$ μm only increases errors of restoration of a microstructure of ashes.
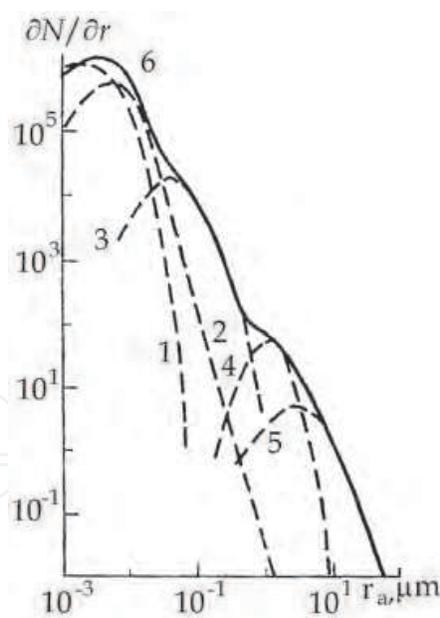

Fig. 22. An example of construction of model of microstructural characteristics (a curve 6) sooty ashes in the form of superposition of definitely weighed fashions curves 1, 2, 3, 4, 5.

Experience of restoration of a microstructure sooty ashes in flames has shown that in flames is present thin-dispersion sooty primary ashes which is generated in flames from a gas phase of products of combustion (Moskalenko et al., 2009) as a result of ionic nucleation, the microstructure and which optical density strongly depend on a chemical composition of gas

fuel. The most probable modal radius of particles of this fraction ashes $r_m=0.003$ μm is received at methane burning in air and in oxygen. A population mean of optical density $\left(\partial\bar{\tau}/\partial L\right)=0.099$ m^{-1}. At propane-butane burning in air the increase in optical density, so $\left(\partial\bar{\tau}/\partial L\right)=0.2$ m^{-1} is observed. The highest values $\left(\partial\bar{\tau}/\partial L\right)=0.4$ m^{-1} is observed in flames at burning of acetylene C_2H_2 when the microstructure sooty ashes is observed most roughly-dispersion. At burning C_2H_2 higher value unburning fuel is observed also.

Microstructure restoration sooty ashes on spectral dependence of factors of radiation and easing of radiation by a flame demands inclusion in consideration of lengths of waves in an ultra-violet part of a spectrum, visible and near infra-red ranges. For definition of a microstructure of huge particles of mineral fraction ashes the additional information on scattering indicatryss of radiation is required. Mineral ash in flames is present at a liquid phase, the complex which indicator of refraction remains to unknown persons that complicates reception of matrixes of scattering of radiation for the purpose of their further use at definition of a microstructure mineral ash in flames. It is important to remember that mineral ash in flames and gas-mains boiler installations it is enriched by carbon (soot) and its radiating properties strongly depend on a subtlety of crushing of firm fuel. Than is thinner highling crushing, the disperse phase of products of combustion has especially high volume factors of absorption (radiation). In process of burning out of particles of firm fuel their size decreases and the specific density of particles that leads to reduction of their radiating ability increases. However, as a result breaking the thaw in the course of them degassing, is generated more a thin dispersion fashion mineral ash with modal radius $r_m\approx0.3$-1 μm, strengthening radiating ability of products of combustion in visible and near infra-red spectrum ranges. Optical characteristics of some equivalent ensemble of spherical particles are defined by a complex indicator of refraction $n=m-ix$, where m and x – its valid and imaginary parts which for a multicomponent chemical composition of particles are described by a parity:

$$m = \frac{\sum\limits_i m_i\cdot\rho_i}{\sum\limits_i\rho_i}\ ;\ x = \frac{\sum\limits_i x_i\cdot\rho_i}{\sum\limits_i\rho_i}\ , \tag{40}$$

where ρ_i – mass concentration of connection i in a particle. Summation extends on all connections which are a part of a particle, including air for friable particles, and also a moisture at the influence account condensation processes on optical characteristics of a disperse phase in atmosphere. In table 4 parameters of models of a microstructure of the particles used as the aprioristic information at restoration of a microstructure of a disperse phase of products of combustion are resulted.

For microstructure definition sooty ashes in flames it is necessary to restore at first its spectral optical density. Function spectral transmission gas components of products of combustion for the chosen optical channels of sounding (optimum for sounding of lengths of waves) and their contribution to spectral intensity of radiation of a flame is for this purpose calculated. Further function of spectral easing of radiation ash and function spectral transmission ashes $\tau_{\lambda a}^a$, caused only is defined by radiation absorption. On the measured spectral functions of easing of radiation τ_λ^a and spectral radiating ability ashes $(1-\tau_{\lambda a}^a)$ it is defined then spectral factors of easing σ_λ^a and absorption (radiation) $\sigma_{\lambda a}^a$ ashes. The restored spectra σ_λ^a and $\sigma_{\lambda a}^a$ serve for microstructure definition ash by optimum

adjustment under spectral dependences σ_λ^a and $\sigma_{\lambda a}^a$. In table 5 the measured spectra σ_λ^a and $\sigma_{\lambda a}^a$ for methane-oxygen, the propane-butane - oxygen and acetylene-air flames are resulted. The restored distributions of a microstructure sooty layer in considered flames are presented in table 6.

№	a	b	c	r_m, μm
1	1	50	0.5	$1.6 \cdot 10^{-3}$
2	0.2	6	0.5	$4.4 \cdot 10^{-3}$
3	1	9	0.5	$4.9 \cdot 10^{-2}$
4	1	7.5	0.5	$9.0 \cdot 10^{-2}$
5	2	12	0.5	$8.9 \cdot 10^{-2}$
6	1.5	6	1	$2.5 \cdot 10^{-1}$
7	0.1	0.5	2	0.3
8	1	1	2	0.3
9	3	6	0.5	1.0
10	3	4	0.5	2.25

Table 4. Parameters of models of a microstructure of particles modified scale - distributions.

п/п	λ, μm	0.287	0.304	0.338	0.55	0.82	1.08	2.62	4.15	9.1
A	σ_λ^a, m^{-1}	0.161	0.154	0.144	0.099	0.072	0.058	0.029	0.019	0.008
	$\sigma_{\lambda a}^a$, m^{-1}	0.105	0.099	0.092	0.065	0.049	0.041	0.022	0.015	0.007
B	σ_λ^a, m^{-1}	0.234	0.230	0.225	0.204	0.174	0.164	0.103	0.082	0.044
	$\sigma_{\lambda a}^a$, m^{-1}	0.126	0.126	0.120	0.115	0.098	0.091	0.065	0.052	0.031
C	σ_λ^a, m^{-1}	0.385	0.398	0.405	0.400	0.380	0.372	0.271	0.225	0.156
	$\sigma_{\lambda a}^a$, m^{-1}	0.190	0.197	0.208	0.210	0.200	0.196	0.158	0.135	0.096

Table 5. The restored spectral optical density sooty ashes σ_λ^a and $\sigma_{\lambda a}^a$ for methane-oxygen (A), the propane-butane - oxygen (B) and acetylene-air (C) flames.

Results of the present measurements of a microstructure sooty ashes are used in calculations of optical characteristics, including spectral factors of easing, scattering, absorption and scattering indicatryss (Moskalenko & Loktev, 2009), in radiating heat exchange and problems of remote sounding.

Sooty ashes in combustion products define unburning fuel and reduce thermal efficiency.

On a microstructure sooty ash probably to define volume of particles ashe:

$$V = A \cdot \int_r \frac{4}{3} \cdot \pi \cdot r^3 \cdot \frac{\partial N}{\partial r} dr \,, \tag{41}$$

where A – normalizing multiplier which is defined on optical density on length of a wave λ =0.55 μm. Knowing density sooty ashes ρ, it is possible to define chemical unburning of fuel $\rho_c \cdot V$.

r, μm	$\partial N/\partial r$			r, μm	$\partial N/\partial r$	
	A	B	C		B	C
0.001	$7 \cdot 10^5$	$1 \cdot 10^5$		0.15	$5 \cdot 10^1$	$2 \cdot 10^3$
0.002	$1.1 \cdot 10^6$	$3 \cdot 10^5$		0.2	$1 \cdot 10^1$	$7 \cdot 10^2$
0.003	$1 \cdot 10^6$	$5 \cdot 10^5$		0.3	$2 \cdot 10^0$	$1.6 \cdot 10^2$
0.004	$9 \cdot 10^5$	$6 \cdot 10^5$	$1 \cdot 10^3$	0.4	$8 \cdot 10^{-1}$	$4.0 \cdot 10^1$
0.006	$8 \cdot 10^5$	$6.5 \cdot 10^5$	$2 \cdot 10^3$	0.6	$3 \cdot 10^{-1}$	$1.5 \cdot 10^1$
0.008	$6 \cdot 10^5$	$6 \cdot 10^5$	$3 \cdot 10^3$	0.8	$1 \cdot 10^{-1}$	6
0.01	$4 \cdot 10^6$	$5 \cdot 10^5$	$5 \cdot 10^3$	1	$3 \cdot 10^{-2}$	2
0.015	$8 \cdot 10^5$	$3 \cdot 10^5$	$1 \cdot 10^4$	1.5		0.6
0.02	$1 \cdot 10^4$	$1 \cdot 10^5$	$1.3 \cdot 10^4$	2		0.2
0.03	$1 \cdot 10^3$	$1.6 \cdot 10^4$	$2 \cdot 10^4$	3		0.06
0.04	$1 \cdot 10^2$	$3 \cdot 10^3$	$1.3 \cdot 10^4$	4		0.02
0.06	$1 \cdot 10^1$	$1 \cdot 10^3$	$8 \cdot 10^3$	6		0.01
0.08	$1 \cdot 10^0$	$6 \cdot 10^2$	$5 \cdot 10^3$	8		0.003
0.1	0.1	$1.5 \cdot 10^2$	$3 \cdot 10^3$	10		0.001
				15		0.0001

Table 6. The restored distributions of a microstructure sooty ashes in methane-oxygen (A), the propane-butane - oxygen (B) and acetylene-air (C) flames.

Concentration of sooty ashes in combustion products strongly depends on structure and a mode of burning of gas fuel and changes in a range of values $4 \times 10^{-7} \div 2.6 \times 10^{-4}/m^3$. The minimum concentration of soot is observed in flame methane-oxygen at factor of surplus of oxygen α =1,03. The maximum concentration is measured for flame acetylene-air.

The received data on microstructure ashes for various flames are used for calculations of matrixes light-scatterig and spectral dependences of factors of easing, absorption and scattering, scattering indicatryss on a spectrum of lengths of waves with their subsequent use in calculations of radiating heat exchange in chambers of combustion of boilers and power technological units. Normalizing optical characteristics sooty ashes it is desirable to carry out with a binding on optical density on length of a wave λ =0.55 μm that allows to use the measured values received in the present work, at calculations of radiating heat exchange in projected objects. Thus it is possible to believe that burning of various components of fuel occurs independently. The weight of each microstructure in optical density sooty ashes is defined by a share of each component in weight of burned fuel.

The microstructure of sooty ashes at movement of products of combustion changes in connection with its burning out thin-dispersion fraction and capture of small particles of soot by large particles in the course of coagulation. These effects can be considered by change of weight of optical density of various fractions sooty ashes on fire chamber volume (Moskalenko et al., 2009).

Trustworthy information on concentration and a microstructure of ash can be received also by the analysis of the selected tests of products of combustion at lower temperatures with

use warmed up multiple-pass cell as the working chamber (Moskalenko et al., 2010). Spectral dependence of easing of radiation bears the information on a microstructure ashes and, hence, about mass concentration ashes.

The knowledge of distribution of mass concentration and fields of temperatures of a disperse phase is of great importance by optimization and heat exchange intensification in top internal devices at coal and black oil burning.

5. Spectral and spatial distribution of thermal radiation in multichamber fire chambers

In the present section possibility of creation of boiler installations with the multichamber fire chambers is considered, allowing essentially to intensify radiating heat exchange in fire chambers and to raise vapor-productivity boiler installations. Now there are two possibilities of increase of efficiency of radiating heat exchange in fire chambers: increase in number of torches in a fire chamber with creation of strong radiating contrasts separate flames on the general thermal background of products of combustion in a fire chamber; creation of multichamber fire chambers where the increase in efficiency radiating cooling is reached at the expense of preservation of dimensions of the top internal chamber by a multichamber design.

The second variant is more effective and supposes wide variety of constructional decisions and allows to design vapor boilers with natural and compulsory circulation, and also to apply the mixed forms of circulation. Multichamber fire chambers can be used for burning firm hydrocarbonic fuels. In this case application in boiler installations of burning of fuel in the cyclonic prefire chambers is perspective, allowing to clear products of combustion of a cindery component. The top internal chamber in this case is actually radiating heat exchanger which for increase of efficiency radiating cooling combustion products is carried out by the multichamber.

The design of a multichamber fire chamber with ascending movement of products of combustion in a fire chamber and vertical development of a flame is most effective (Moskalenko & Zaripov, 2008; Moskalenko et al., 2008) with matrix burning device, the general gas collector for oxidizer giving (air or oxygen) and a collector for giving of gas fuel to multirow to torches. Burning devices are expedient for the transfer out with a radiator for its cooling by water on an independent circulating contour. At use the hearth burning devices providing maximum time of stay of products of combustion in a fire chamber. For the given height of a fire chamber and its sizes increase vapor-productivity the boiler can be reached by increase in speed radiating cooling $\partial T/\partial t$ which is reached by decrease in cross-section section of separate chambers in a multichamber fire chamber.

On fig. 23 dependence of the relation of speed radiating cooling $\partial T(L)/\partial t$ by the speed $(\partial T(L)/\partial t)_{max}$ from distance L between walls of a multichamber fire chamber is presented.

From the presented drawing it is visible that speed $\partial T(L)/\partial t$ reaches the maximum value at small distances L between fire chamber walls when function spectral transmission aspires to unit. With increase in distance L between walls of a fire chamber speed radiating cooling $\partial T(L)/\partial t$ decreases and, hence, for achievement of temperature T_{uh}=const on an exit from a fire chamber time $\Delta t(L)$ decreases with increase vapor-productivity a boiler. The less size L in a multichamber fire chamber, the at smaller height H from hearth fire chambers is reached value T_{uh}. The full value radiating cooling $\Delta T = T_a - T_{uh}$ depends on an arrangement of the torches forming the ascending stream of a flame.
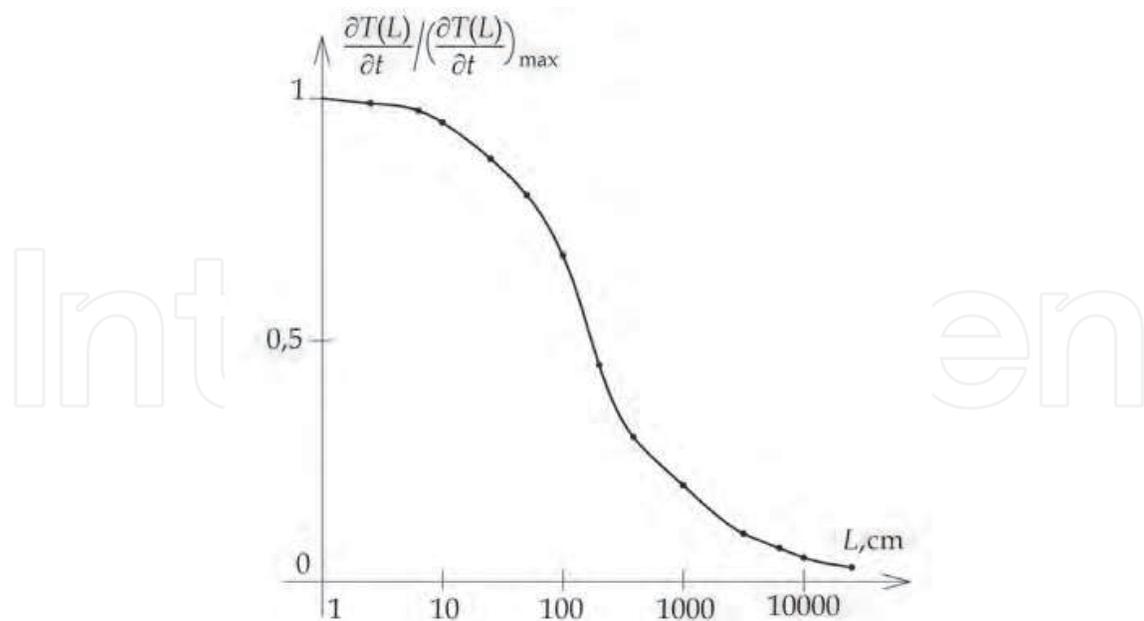
Fig. 23. Relative dependence of average speed radiating cooling $\dfrac{\partial T(L)}{\partial t}\bigg/\left(\dfrac{\partial T(L)}{\partial t}\right)_{\max}$ from

distance L between walls heatsusceptibility surfaces. Fuel – natural gas, the hearth burning device of matrix type with multirow torches, factor of surplus of air α =1,03.

For formation short flames it is expedient to use multirow burning devices the height of an ardent zone in which depends on diameter of tubes. For definition of height of an ardent zone in the presented calculations the theory of similarity and really observable heights of a flame was used. At diameter of tubes D=8 mm through which fuel (diameter of an individual nozzle) height of an ardent zone of products of combustion arrives makes 70 cm. With increase in diameter D the height of an ardent zone increases and, hence, its speed nonequilibrium radiating cooling decreases.

At modernization of existing steam-boilers with their transfer into an operating mode of multichamber fire chambers it is possible to increase in 2-3 times them vapor-productivity. Application of multichamber fire chambers in case of use of gas fuel allows to reduce steam-boiler dimensions (at the same vapor-productivity).

Designing of multichamber fire chambers demands consideration of technological aspects of their manufacturing about economic efficiency of manufacture. From our point of view manufacturing of a boiler of the cylindrical form of tower type with multichamber fire chambers and rectangular multichamber fire chambers should be rather effective. High thermal loadings of the bottom part heatsusceptibility surfaces of a steam-boiler demand optimization of loading of circulating contours of the heat-carrier and designs heatsusceptibility the surfaces providing their steady hydrodynamic characteristics.

It is necessary to notice that in a homogeneous medium of the infinite sizes of radiating heat exchange doesn't exist.

5.1 Mathematical model of the transfer over of nonequilibrium radiation in flames and high-temperature diphasic mediums

Errors of calculations at the decision of problems of radiating heat exchange are defined by function spectral transmission in structurally non-uniform multicomponent mediums.

Generally at function evaluation spectral transmission $\tau_{\Delta v}$ it is necessary to allocate contributions to the absorption, caused by wings of the remote spectral lines of the various atmospheric gases $\tau_{\Delta v}^{k}$, the absorption induced by pressure $\tau_{\Delta v}^{n}$, selective absorption of the spectral lines entering into the chosen spectral interval (owing to distinctions in these cases of function spectral transmission $\tau_{\Delta v}$ from the maintenance absorbing (radiating) gas, effective pressure P, and temperature T). Then for the set component function spectral transmission is defined as product of three considered above functions. Similar division allows providing universality of the description $\tau_{\Delta v}$ for any almost realized atmospheres of top internal devices of the present and the future workings out.

For multicomponent atmosphere $\tau_{i\Delta v}$ it will be defined as product $\prod_{i} \tau_{i\Delta v}$, where i - component number. Legitimacy of this law is checked up experimentally and follows from independence of thin structure of spectra of the various absorbing (radiating) components which are a part of torches and oven atmosphere.

Let's believe that structural characteristics of the top internal chamber are known. For the account of nonequilibrium processes of radiation in a torch we will express function of a source for nonequilibrium radiation of a component i a torch in a kind

$$B_{i\lambda}(T) = B_{\lambda}^{abb}(T) \cdot \eta_{i\lambda}(T),$$ (42)

Where $\eta_{i\lambda}(T)$ – factor of nonequilibrium radiations for a component i.

Let's consider at first the elementary case of the absorbing medium: radiation scattering is absent or radiation scattering is neglected. We will assume that the temperatures of walls T_g is known, distribution of temperature T on volume of the top internal chamber and a field of concentration of gas and disperse components are set. Let O - a supervision point in the top internal chamber, K - a point of intersection of a vector of supervision l with a surface of the top internal chamber. A vector of scanning of volume of space from point K we will designate L. We will assume also that a wall surface is Lambert's. Then spectral intensity of thermal radiation in a direction l will be defined by a parity:

$$J_{\Delta\lambda}(l) = \int_{0}^{L_k} \sum_{i} B_{\lambda}\left[T(l)\right] \eta_{i\lambda}\left[T(l)\right] \frac{d\tau_{i\Delta\lambda}}{dl} \prod_{k\neq i} \tau_{k\Delta\lambda}(l)\,dl + \left(1-\delta_{\lambda}^{k}\right) B_{\lambda}\left(T^{k}\right) \tau_{\Delta\lambda}\left(l_{0}^{k}\right) +$$

$$+\frac{\delta_{\lambda}^{k}}{\pi} \int_{0}^{2\pi}\int_{0}^{L_k} B_{\lambda}\left[T(L)\right] \sum_{i} \eta_{i\lambda}\left[T(L)\right] \frac{d\tau_{i\Delta\lambda}}{dl}\left[L(\theta,\varphi)+l_{0}^{k}\right] \cdot \prod_{k\neq i} \tau_{k\Delta\lambda}\left[L(\theta,\varphi)+l_{0}^{k}\right] dLd\Omega +$$ (43)

$$+\frac{\delta_{\lambda}^{k}}{\pi} \int_{0}^{2\pi}\left[1-\delta_{\lambda}^{g}\right] B_{\lambda}\left[T(L_g)\right] \tau_{\Delta\lambda}\left(l_{0}^{k}+l_{k}\right) d\Omega,$$

where $T(l)$ – temperature of medium along an optical way l; $B_{\lambda}\left[T(l)\right]$ – spectral brightness of radiation of absolutely black body at temperature T in a point l; δ_{λ} – spectral factor of reflection of a wall; l_{0}^{k} – an optical way between points O and K; T^{k} – temperature in point K; $\tau_{\Delta\lambda}(l)$ – function spectral transmission for an optical way l in a spectral interval in width $\Delta\lambda$; λ – length of a wave; T (L_g) – temperature in a point of intersection of vector L with a wall surface; $d\Omega$ – a space angle element; θ, φ – antiaircraft and azimuthally corners,

accordingly; $\tau_{\Delta\lambda}(L+l)$ means function spectral transmission along an optical way (L+l); the index «g» means wall border.

In the ratio (43) product undertakes on all components $k \neq i$, including ashes,

$$\tau_{\Delta\lambda} = \prod_i \tau_{\Delta\lambda i} , \qquad (44)$$

where $\tau_{\Delta\lambda i}$ - function of spectral transmission for *i*-th component as gas, so disperse phases of top internal atmosphere. For gas components function $\tau_{\Delta\lambda i}$ are calculated on a two-parametrical method of equivalent mass, considered in section 2.2.

For the account of absent-minded radiation, we will choose the beginning of coordinates at the bottom of a fire chamber. An axis of coordinates z we will choose in conformity with symmetry of an ascending stream of products of combustion. We will enter polar system of coordinates. We will designate a supervision point z_n with antiaircraft θ_0 and azimuthal φ_0 supervision corners; θ, φ – flowing antiaircraft and azimuthally corners of integration on space. Then any point in fire chamber space will be characterized by height z concerning a bottom of a fire chamber and corners θ, φ, and a surface limiting space of a fire chamber – coordinates z_g, θ, φ. The radiation going to the top hemisphere from a point of supervision z_n, we will name ascending with intensity $J\uparrow$. The radiation going to the bottom hemisphere with intensity $J\downarrow$ we will name descending. The corner of scattering of radiation $\Psi(\theta_0, \varphi_0, \theta, \varphi)$ depends as on a supervision direction θ_0, φ_0, and current corners of integration θ, φ of absent-minded radiation. We will assume further that the fire chamber surface has temperature $T(z_g, \theta, \varphi)$ and spectral factor of reflection $\delta_\lambda(z_g, \theta, \varphi)$, λ - length of a wave of radiation.

Let's enter further scattering indicatryss $f(z,\Psi)$ in such a manner that

$$\int d\phi \int f(z,\Psi) \sin\Psi d\Psi = 1 . \qquad (45)$$

Let $\tau_{\Delta\lambda a}(l)$ - function spectral transmission at the expense of absorption of radiation of a gas phase of top internal atmosphere and its disperse phase, $\tau_{\lambda s}^a(l)$ - function spectral transmission (easing) only at the expense of scattering of radiation of a disperse phase of top internal atmosphere, $\tau_{\lambda a}^a(l)$ - function spectral transmission at the expense of absorption of radiation by aerosols for which following parities are fair:

$$\tau_{\lambda a}^a(l) = \exp\left[-\sigma_{\lambda a}^a \int_l \sigma_0^a(l) dl \right], \qquad (46)$$

$$\tau_{\lambda s}^a(l) = \exp\left[-\sigma_{\lambda s}^a \int_l \sigma_0^a(l) dl \right], \qquad (47)$$

$$\tau_{\Delta\lambda a}^a(l) = \tau_{\lambda a}^a(l) \prod_i \tau_{\Delta\lambda i}^a(l), \qquad (48)$$

where l - an optical way which runs radiation beam, $\sigma_{\lambda a}^a, \sigma_{\lambda s}^a$ - spectral normalizing volume factors of absorption and aerosol scattering, $\sigma_{\lambda 0}^a(l)$ - volume factor of easing of

radiation by an aerosol on length of a wave λ =0,55 μm, $\tau_{\Delta\lambda i}(l)$ - function spectral transmission for i-th component of a gas phase of atmosphere for spectral intervals in width Δ with the center λ which are calculated on a two-parametrical method of equivalent mass. Let's choose a supervision direction l which will cross borders of a surface of a fire chamber for the top hemisphere $z_g^+(\theta_0,\phi_0)$ and for the bottom hemisphere $z_g^-(\theta_0,\phi_0)$ concerning a horizontal plane $z = z_n$.

Then for intensity of ascending radiation $J_{\Delta\lambda}^{\uparrow}$ in approach of unitary scattering in a direction θ_0, ϕ_0, in a point z_n

$$J_{\Delta\lambda}^{\uparrow} = J_{1\Delta\lambda}^{\uparrow} + J_{2\Delta\lambda}^{\uparrow} + J_{3\Delta\lambda}^{\uparrow} + J_{4\Delta\lambda}^{\uparrow} + J_{5\Delta\lambda}^{\uparrow}, \tag{49}$$

and for intensity of descending radiation

$$J_{\Delta\lambda}^{\downarrow} = J_{1\Delta\lambda}^{\downarrow} + J_{2\Delta\lambda}^{\downarrow} + J_{3\Delta\lambda}^{\downarrow} + J_{4\Delta\lambda}^{\downarrow} + J_{5\Delta\lambda}^{\downarrow}, \tag{50}$$

Where $J_{1\Delta\lambda}^{\downarrow}$ - own descending radiation of the medium of the top internal chamber in a supervision point; $J_{2\Delta\lambda}^{\downarrow}$ - radiation of a wall of the top internal chamber in the supervision direction, weakened by top internal atmosphere; $J_{3\Delta\lambda}^{\downarrow}$ - disseminated in a direction of supervision the radiation which is starting with volume of top internal atmosphere (from point volume); $J_{4\Delta\lambda}^{\downarrow}$ - absent-minded radiation of all walls of the fire chamber, reflected from a point l^g on a wall in a supervision direction; $J_{5\Delta\lambda}^{\downarrow}$ - own radiation of all walls of the chamber, weakened by oven atmosphere and reflected from a point on a wall in a supervision direction. The physical sense of components intensitys in the ratio (49) for ascending radiation is similar.

For nonequilibrium radiation source function is various for various radiating components and can change within top internal volume and on a spectrum of lengths of waves of electron-vibrational transitions of molecules. If sizes $\eta_{i\lambda}$ for components i are known, in the intensity equations it is necessary to enter summation of radiations on components i under the badge of integrals, having replaced size $B_\lambda(T)$ in size $B_\lambda(T)\cdot\eta_{i\lambda}$. Then for intensity of ascending radiation:

$$J_{1\Delta\lambda}^{\uparrow} = \int\limits_{z_g}^{z_n} \sum_i \frac{B_\lambda\left[T(z),\theta_0,\phi_0\right]\cdot\eta_{i\lambda}\left[T(z),\theta_0,\phi_0\right]\tau_{\lambda s}^a(z,\theta_0,\phi_0)\dfrac{\partial\tau_{i\Delta\lambda a}(z,z_n,\theta_0,\phi_0)}{\partial z}}{\prod\limits_{k\neq i}\tau_{i\Delta\lambda a}^a(z,z_n,\theta_0,\phi_0)}\, dz, \tag{51}$$

$$J_{2\Delta\lambda}^{\uparrow} = B_\lambda\left[T_g\left(z_g^-,\theta_0,\phi_0\right)\right]\tau_{\lambda s}\left(z_g^-,\theta_0,\phi_0\right)\tau_{\Delta\lambda a}\left(z_g^-,\theta_0,\phi_0\right), \tag{52}$$

$$J_{3\Delta\lambda}^{\uparrow} = \int\limits_0^{2\pi}\partial\phi\int\limits_{-\pi/2}^{\pi/2}\sin\theta\,\partial\theta\int\limits_{z_g^-}^{z_n} f_\lambda\left[z,\psi\left(\theta,\phi,\theta_0,\phi_0\right)\right]\frac{\partial}{\partial z}\tau_{\lambda s}\left[z,z_g,(\theta,\phi),\theta,\phi;z,z_n,\theta_0,\phi_0\right]\cdot$$

$$\cdot \int_{z_g^+}^z \left\{ \sum_i B_\lambda \big[T(z,\theta,\phi) \big] \eta_{i\lambda} \big[T(z,\theta,\phi) \big] \frac{\partial}{\partial z} \tau_{i\Delta\lambda\alpha} \big[z,z',\theta,\phi;z_n,z,\theta_0,\phi_0 \big] \prod_{k\neq i} \tau_{k\Delta\lambda\alpha} \big(z,z',\theta,\phi;z_n,z,\theta_0,\phi_0 \big) \right\} dz'dz, \quad (53)$$

$$J_{4\Delta\lambda}^{\uparrow} = \frac{\delta_{\lambda g}\big(z_g^-,\theta_0,\varphi_0 \big)}{\pi} \int_0^{2\pi} d\varphi \int_{-\pi/2}^{\pi/2} \sin\theta d\theta \int_{z_g^-}^{z_n} f_\lambda \big[z,\Psi(\theta,\varphi,\theta_0,\varphi_0) \big] \frac{\partial}{\partial z} \tau_{\lambda s} \big[z,z_g,(\theta,\varphi),\theta,\varphi;z,z_n,\theta_0,\varphi_0 \big] \cdot \quad (54)$$

$$\cdot \tau_{\Delta\lambda a} \big[z,z_g,(\theta,\varphi),\theta,\varphi;z,z_n,\theta_0,\varphi_0 \big] \cdot \big[1 - \delta_{\lambda g}(z,\theta_0,\varphi_0) \big] B_\lambda^g \big[T(\theta,\varphi) \big] dz,$$

$$J_{5\Delta\lambda}^{\uparrow} = \frac{\delta_\lambda\big(z_g^-,\theta_0,\varphi_0 \big)}{\pi} \int_0^{2\pi} d\varphi \int_{-\pi/2}^{\pi/2} \big\{ 1 - \delta_\lambda\big(z_g,(\theta,\varphi) \big) \big\} \cdot B_\lambda^g \big[T(\theta,\varphi) \big] \tau_{\lambda s} \big[z_g^-,z_g(\theta,\varphi),\theta,\varphi;z_g^-,z_n,\theta_0,\varphi_0 \big] \cdot \quad (55)$$

$$\cdot \tau_{\Delta\lambda a} \big[z_g^-,z_g(\theta,\varphi),\theta,\varphi;z_g^-,z_n,\theta_0,\varphi_0 \big] d\theta,$$

where summation is carried out on all components i, and product – on all components $k \neq i$; z_g^- means that fire chamber borders are located below supervision height z_n; $\delta_{\lambda g}^+$ means reflection factor on border of the fire chamber located at height $z_g > z_n$.

For intensity of descending radiation $J_{1\Delta\lambda}^{\downarrow}$ it is easy to write parities, similar (50-54),

$$J_{1\Delta\lambda}^{\downarrow} = \int_{z_g^+}^{z_n} \sum_i B_\lambda \big[T(z),\theta_0,\varphi_0 \big] \cdot \eta_{i\lambda} \big[T(z),\theta_0,\varphi_0 \big] \tau_{\lambda s}^a (z,\theta_0,\varphi_0) \frac{\partial \tau_{i\Delta\lambda a}\big(z,z_n,\theta_0,\varphi_0 \big)}{\partial z} \prod_{k\neq i} \tau_{i\Delta\lambda a}^a \big(z,z_n,\theta_0,\varphi_0 \big) dz, \quad (56)$$

$$J_{2\Delta\lambda}^{\downarrow} = B_\lambda \big[T_g\big(z_g^+,\theta_0,\varphi_0 \big) \big] \big[1 - \delta_\lambda\big(z_g^+,\theta_0,\varphi_0 \big) \big] \tau_{\lambda s}\big(z_g^+,\theta_0,\varphi_0 \big) \tau_{\Delta\lambda a}\big(z_g^+,\theta_0,\varphi_0 \big), \quad (57)$$

$$J_{3\Delta\lambda}^{\downarrow} = \int_0^{2\pi} d\varphi \int_{-\pi/2}^{\pi/2} \sin\theta d\theta \int_{z_g^+}^{z_n} f_\lambda \big[z,\Psi(\theta,\varphi,\theta_0,\varphi_0) \big] \frac{\partial}{\partial z} \tau_{\lambda s} \big[z,z_g,(\theta,\varphi),\theta,\varphi;z,z_n,\theta_0,\varphi_0 \big] \cdot \quad (58)$$

$$\cdot \int_{z_g^+}^z \left\{ \sum_i B_\lambda \big[T(z,\theta,\phi) \big] \eta_{i\lambda} \big[T(z,\theta,\phi) \big] \frac{\partial}{\partial z} \tau_{i\Delta\lambda\alpha} \big[z,z',\theta,\phi;z_n,z,\theta_0,\phi_0 \big] \prod_{k\neq i} \tau_{k\Delta\lambda\alpha} \big(z,z',\theta,\phi;z_n,z,\theta_0,\phi_0 \big) \right\} dz'dz, \quad (59)$$

$$J_{4\Delta\lambda}^{\downarrow} = \frac{\delta_{\lambda g}\big(z_g^+,\theta_0,\varphi_0 \big)}{\pi} \int_0^{2\pi} d\varphi \int_{-\pi/2}^{\pi/2} \sin\theta d\theta \int_{z_g^+}^{z_n} f_\lambda \big[z,\Psi(\theta,\varphi,\theta_0,\varphi_0) \big] \frac{\partial}{\partial z} \tau_{\lambda s} \big[z,z_g,(\theta,\varphi),\theta,\varphi;z,z_n,\theta_0,\varphi_0 \big] \cdot \quad (60)$$

$$\cdot \tau_{\Delta\lambda a} \big[z,z_g,(\theta,\varphi),\theta,\varphi;z,z_n,\theta_0,\varphi_0 \big] \cdot \big[1 - \delta_{\lambda g}(z,\theta_0,\varphi_0) \big] B_\lambda^g \big[T(\theta,\varphi) \big] dz,$$

$$J_{5\Delta\lambda}^{\downarrow} = \frac{\delta_\lambda\big(z_g^+,\theta_0,\varphi_0 \big)}{\pi} \int_0^{2\pi} d\varphi \int_{-\pi/2}^{\pi/2} \big\{ 1 - \delta_\lambda\big(z_g,(\theta,\varphi) \big) \big\} B_\lambda^g \big[T(\theta,\varphi) \big] \cdot \tau_{\lambda s} \big[z_g^+,z_g(\theta,\varphi),\theta,\varphi;z_g^+,z_n,\theta_0,\varphi_0 \big] \cdot \quad (61)$$

$$\cdot \tau_{\Delta\lambda a} \big[z_g^+,z_g(\theta,\varphi),\theta,\varphi;z_g^+,z_n,\theta_0,\varphi_0 \big] d\theta.$$

Processes of nonequilibrium radiation at burning hydrocarbonic fuels practically aren't developed also their influence on radiating cooling a torch of top internal space practically isn't studied. From the most general reasons of formation of electron-vibrational spectra it is

possible to draw a conclusion that the greatest influence on process of radiating heat exchange in fire chambers nonequilibrium renders radiations at burning of gaseous hydrocarbonic fuel and black oil which incorporate S-contents and N-contents the components forming nonequilibrium radiation of a high-temperature kernel of a torch.

At the decision of problems of radiating heat exchange in boilers operate integrated intensity thermal radiation which are defined by integration spectral intensitys thermal radiation on a spectrum of lengths of waves λ:

$$J^{\uparrow}(z_n,\theta_n,\phi_n) = \int_0^{\infty} J_{\lambda}^{\uparrow}(z_n,\theta_n,\phi_n)d\lambda , \tag{62}$$

$$J^{\downarrow}(z_n,\theta_n,\phi_n) = \int_0^{\infty} J_{\lambda}^{\downarrow}(z_n,\theta_n,\phi_n)d\lambda . \tag{63}$$

Knowing sizes $J^{\uparrow\downarrow}(z_n,\theta_n,\phi_n)$, it is possible to define streams of thermal radiation on any direction including on heatsusceptibility surfaces, having executed spatial integration $J^{\uparrow\downarrow}$ within a space angle 2π. In particular, for streams of descending and ascending radiation

$$F^{\uparrow\downarrow}(z) = \int_0^{2\pi} J^{\uparrow\downarrow}(z,\theta,\phi)d\Omega , \tag{64}$$

where $d\Omega$ – a space angle element. Radiating change of temperature will be defined from a parity

$$\frac{\partial T(z,\theta,\phi)}{\partial t} = \frac{1}{\rho(z,\theta,\phi)C_p(z,\theta,\phi)} \cdot \frac{\partial F(z,\theta,\phi)}{\partial z} , \tag{65}$$

where $\rho(z,\theta,\phi), C_p(z,\theta,\phi)$ - accordingly density and a thermal capacity in a local point with coordinates z, θ, φ,

$$F(z,\theta,\varphi) = F^{\uparrow}(z,\theta,\varphi) - F^{\downarrow}(z,\theta,\varphi).$$

If heat exchange process is stationary, $dT(z,\theta,\phi)/dz = const$ for any local volume with coordinates z, θ, φ. If heat exchange process is not stationary there are time changes of temperature in the local volumes which time trend can be calculated by application of iterative procedure of calculations on each time step i so

$$T_{i+1}(z,\theta,\phi) = T_i(z,\theta,\phi) + \Delta t \frac{dT_i(z,\theta,\phi)}{dt} . \tag{66}$$

However thus it is necessary to take into consideration and influence of other mechanisms of heat exchange: diffusion, turbulent diffusion, convective heat exchange.

Most intensively radiating cooling it is shown in a torch kernel, in this connection its temperature always below theoretical on 15-20 %. The last means that during combustion of fuel the torch considerably cools down as a result of radiating cooling. Degree radiating cooling a torch is maximum, if the stream expires in free atmosphere. In the closed volume

of a fire chamber radiating cooling increases with growth of temperature of a torch, degree of its blackness at the expense of absorption of radiation by gas and disperse phases of products of combustion and decreases at rise in temperature heatsusceptibility surfaces and their factors of reflection. In cold zones of a fire chamber can take place and radiating heating if in them active components contain optically. If there are temperature inversions in temperature distributions in zones of temperature inversions radiating heating or easing radiating cooling also can be observed.

Full radiating cooling combustion products in a fire chamber depends on time of their stay in top internal volume and, hence, from speed of movement of products of combustion $V(z)$ in a fire chamber which can change on fire chamber height. Full radiating cooling combustion products ΔT it is defined by the formula:

$$\Delta T = \int_0^H \frac{1}{V(z)} \cdot \frac{\partial T}{\partial z} dz \,, \tag{67}$$

where H is fire chamber height.

Let's analyze the physical processes proceeding in the top internal chamber under the influence of nonequilibrium short-wave radiation which is generated in ultra-violet and visible parts of a spectrum as a result of a relaxation of the raised molecules formed at burning of fuel. If the difficult molecule is formed in wild spirits and dissociates on unstable short-living splinters also its splinters will be in wild spirits and to generate nonequilibrium short-wave radiation. Owing to small time of life of these connection spectral lines of nonequilibrium radiation will be much wider, than for equilibrium radiation, and can create the diffuse spectra of radiation which are not dependent from widening of pressure. Functions spectral transmission for the nonequilibrium medium submits to the law of Buger:

$$\tau_{\Delta v}(L) = \int_L \exp\left[-k_v(L)\right] dL \,, \tag{68}$$

where $k_v(L)$ - absorption factor, v - the wave number, and integration is carried out along optical way L to a torch kernel. Vibrational and rotary structures of a spectrum of nonequilibrium radiation it will be washed away and poorly expressed. There is a basis to believe, as nuclear spectra of elements also can be nonequilibrium that proves to be true on an example of nuclear spectra of the sodium which lines of radiation have appeared nonequilibrium and at high temperatures can't be used for definition of temperature of a flame. Hence, probably to expect presence of photochemical reactions under the influence of the short-wave radiation, products of combustion essentially influencing a chemical composition in the top internal chamber.

Feature of nonequilibrium processes of radiation is considerable cooling zones of chemical reactions in time $\approx 10^{-4}$ sec, commensurable in due course courses of chemical reactions. In this connection the equilibrium temperature of a flame considerably decreases that leads to much lower concentration of a monoxide of nitrogen NO. Really, it agree (Zel'dovich et al., 1947)

$$[NO]_{\max} = 4.6 \sqrt{C_{N_2} C_{O_2}} \exp\left(\frac{-21500}{R T_{\max}}\right), \tag{69}$$

where at fuel burning in air

$$C_{O_2} = 21(\alpha - 1)V_0 \big/ \left(1 + \alpha V_0\right)$$
$$C_{N_2} = 79\alpha V_0 \big/ \left(1 + \alpha V_0\right)$$

(70)

Here T_{max} - the maximum absolute temperature in peaks of volumes of chemical reactions, R - a gas constant, V_0 - theoretically necessary quantity of air for fuel burning, α - factor of surplus of air. At high temperatures real concentration NO in combustion products on an order and lower, than intended under formulas (69, 70) that from our point of view is caused nonequilibrium radiating cooling peaks of chemical reactions. And real concentration NO can depend on depth of turbulence burning and a spectrum of whirls.

By consideration of radiating heat exchange in the top internal chamber with torch burning of firm fuel in the twirled streams it is necessary to take into consideration the phenomenon of separation of particles when the largest particles are taken out in peripheral zones of a fire chamber where, settling, can grasp sooty ashes, formed as a result of pyrolysis in cold zones of a fire chamber, and then to flow down in a cold funnel.

Considering dependence of absorption of nonequilibrium radiation by combustion products, we will pay attention to strengthening of absorption with increase in capacity of the top internal chamber. Hence, with increase in capacity of a fire chamber nonequilibrium radiation in a greater degree passes in thermal energy of particles of fuel and thermal energy of products of combustion. Nonequilibrium radiating cooling decreases also and concentration NO_x increases with increase in capacity of a fire chamber that is really observed by results of statically provided supervision.

Let's pay attention to results of measurements of a chemical composition of products of combustion of wood (Moskalenko et al., 2010) when raised concentration NO_2 have been found out. If at burning of black oil and gases the relation of concentration $C(NO_2)/C(NO) \approx$ 0.1, at burning of wood the relation of concentration $C(NO_2)/C(NO) \approx 1/3$. It means that the increase in concentration NO_2 causes increase in intensity of the nonequilibrium radiation reducing temperature of a flame, and, hence, leads to reduction of concentration NO. Considering optical properties of a disperse phase depending on a microstructure of liquid or firm fuel at chamber burning, it is necessary to notice that concentration NO will increase in smoke gases with increase in a subtlety of scattering of liquid fuel and crushing of firm fuel. From the point of view of ecological influence of atmospheric emissions on flora and fauna expediently chamber burning of fuel of rough crushing and scattering. Besides, from the point of view of minimization of anthropogenous influences on medium it is expedient to burn fuel at lower pressure as nonequilibrium radiating cooling amplifies with pressure decline in a fire chamber (process of suppression of a chemical luminescence with pressure decline it is weakened).

Presence chemical unburning leads to formation of heavy hydrocarbons in combustion products (especially benzologies) that causes suppression of nonequilibrium radiation in a fire chamber. The last can be formed in interfaces of the top internal chamber and weaken heatsusceptibility of screens owing to strong absorption of ultra-violet radiation.

Presence of connections of sulfur in fuel leads to occurrence of nonequilibrium radiation SO_2 in the field of a spectrum $\lambda < 0.4$ μm which reduces flame temperature, and, hence, and concentration NO_x.

5.2 Modelling of radiating heat exchange in multichamber fire chambers

Let's consider results of modeling of radiating heat exchange of multichamber fire chambers taking into account nonequilibrium processes of radiation (Moskalenko et al., 2009), section 5.1 executed on algorithms for diphasic structurally non-uniform medium of top internal space of the chamber of combustion.

On fig. 24 for an example results of calculations of vertical profiles of speed radiating cooling $\partial T(z)/\partial t$, $\partial T(z)/\partial z$ and stationary distribution of temperature $T(z)$ from fire chamber height z over cuts of capillaries matrix burning devices are illustrated. Fuel is natural gas of a gas pipeline of Shebalovka-Brjansk-Moskva, the size of horizontal section of a cell of a multichamber fire chamber 1,25x1,6 m^2.

Speed of giving of products of combustion on an initial site of a fire chamber makes values υ_0=25 m/s and υ_0=20 m/s at pressure in a fire chamber $1 \cdot 10^5$ Pa. Height of an ardent zone $\Delta z = 0,7$ m. In calculations are considered equilibrium and nonequilibrium processes of radiation on the algorithms considered above. It is supposed that process of burning of various components of gas fuel occurs independently at optimum value of factor of surplus of air α =1,03.

The microstructure sooty ashes is measured at burning (to look section 4) methane, propane-butane and acetylene (Moskalenko et al., 2010). Optical characteristics sooty ashes are calculated for the measured microstructures of a disperse phase of products of combustion. Volume factors of easing, absorption and scattering normalized on the measured values of optical density ash (Moskalenko et al., 2009).
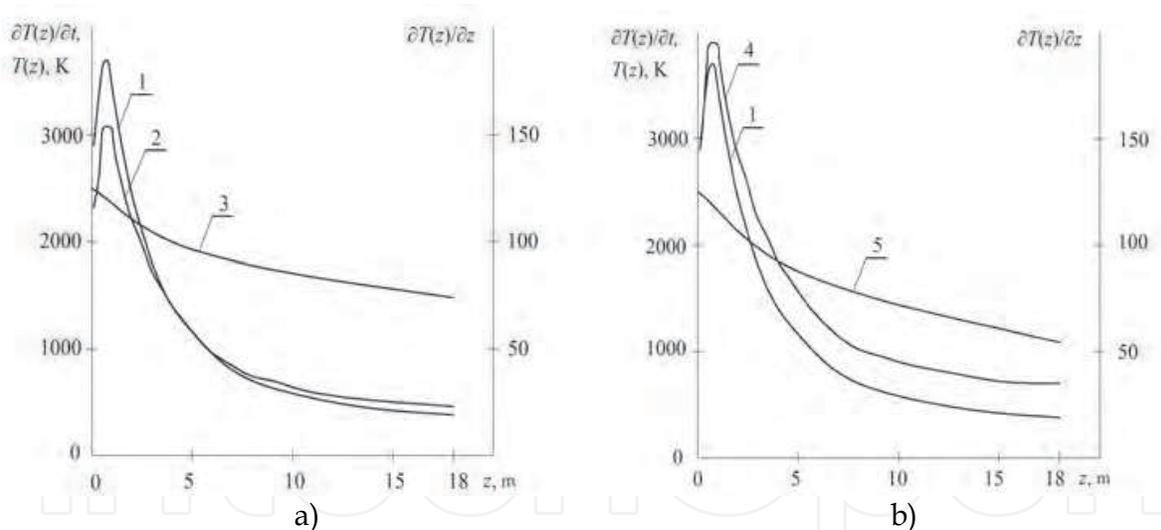
Fig. 24. Results of calculation of radiating heat exchange in a multichamber fire chamber with the size of horizontal section of a cell 1,25x1,6 m^2 for initial average speed of a current of products of combustion of 25 m/s (a) and 20 m/s (b). $\partial T(z)/\partial t$, $\partial T(z)/\partial z$ - speeds radiating cooling, $T(z)$ – a temperature profile of average on section of temperature depending on height z over cuts of capillaries multirow torches. 1– $\partial T(z)/\partial t$; 2 − $\partial T(z)/\partial z$ for initial average speed of a current of products of combustion of 25 m/s; 3 – $T(z)$ for initial average speed of a current of products of combustion of 25 m/s; 4 − $\partial T(z)/\partial z$ for initial average speed of a current of products of combustion of 20 m/s; 5 – $T(z)$ for initial average speed of a current of products of combustion of 20 m/s.

On fig. 25 examples of spectral and spatial distributions of thermal radiation on heatsusceptibility surfaces of a cell of a multichamber fire chamber by results of the closed modeling of process of radiating heat exchange with calculation of speed radiating cooling products of combustion and their temperature depending on height over cuts of capillaries multirow a torch forming ascending streams of a flame are resulted. Horizontal section of a cell of a multichamber fire chamber – a square with the party of 1,4 m. Fuel – natural gas of a gas pipeline of Shebalovka-Brjansk-Moskva, factor of surplus of air α = 1,03. Average initial speed of products of combustion makes 25 m/s. Pressure in a fire chamber – 10^5 Pa. The executed calculations of heatsusceptibility surfaces show that the greatest thermal loading the bottom part of lateral screens and heatsusceptibility is exposed to a surface hearth of fire chambers. So, on the central axis of the lateral screen at heights 1, 7, 17 meters from a cut of capillaries of a torch falling streams of heat make accordingly 260,313; 99,709; 48,387 kW/m². For the center hearth of fire chambers the falling stream of heat answers value of 249,626 kW/m², and the ascending stream of heat at height h = 18 m on an axis of a cell of a fire chamber makes 41,115 kW/m². A full stream

$$ F = \int_s F(S)dS = \sum_i V_i \int_0^h C_{ip}[t(z)]dz , \tag{71} $$

where C_{ip}, V_i – accordingly a thermal capacity at the constant pressure, answering to temperature t in a point z and volume for a component i combustion products. This condition at the closed modeling of heat exchange is carried out with a margin error 1 %. In approach of "gray" radiation when calculations are carried out under the law of Buger, overestimate heatsusceptibility on 15 % is observed. The account of effective pressure reduces an error of calculation full heatsusceptibility by 5-6 %. At use of a two-parametrical method of equivalent mass in calculations of function spectral transmission at modeling of a disperse phase of products of combustion in the present calculations it is supposed that burning of each component of fuel occurs independently that allows to use optical density sooty ashes by results of measurements on ardent measuring complexes. For methane, propane-butane, acetylene the optical density on length of a wave 0,55 μm is accepted according to equal 0,1; 0,2; 0,4 m⁻¹ in an ardent zone. Above an ardent zone it is observed exponential recession of numerical density thin-dispersion ashes with height in connection with its burning out. More rougly-dispersion fractions 2,3 sooty ashes don't burn out, and their distribution doesn't depend on height. The contribution of each fraction ashes is normalized according to volume concentration CH_4, propane-butane, C_2H_2.

On fig. 26 distribution of an integrated stream of the radiation calculated taking into account absorption (radiation) by basic optically by active components of products of combustion on lateral walls of a cell of a multichamber fire chamber depending on height of a fire chamber in case of weak approximation is illustrated. On fig. 27 distribution of an integrated stream of radiation to lateral walls of a cell of a multichamber fire chamber depending on height the fire chambers calculated with use of function spectral transmission on a two-parametrical method of equivalent mass is presented. On fig. 28 distribution of an integrated stream of the radiation calculated taking into account absorption (radiation) by basic optically active components of products of combustion, but without effective pressure is resulted. For the given design of a multichamber fire chamber the contribution of nonequilibrium radiation to radiating heat exchange makes 7,5 % from a full stream. Absence of the account of

A-a)

A-b)

A-c)

A-d)
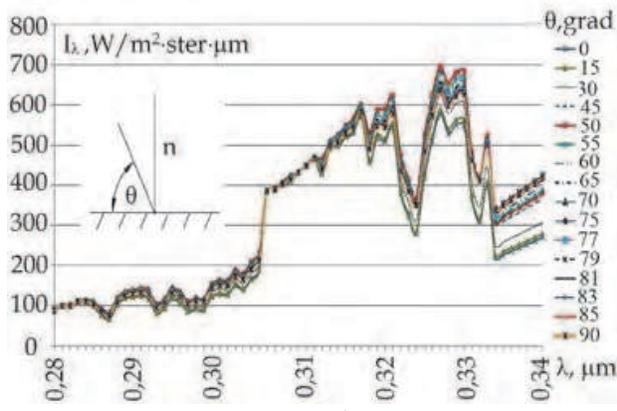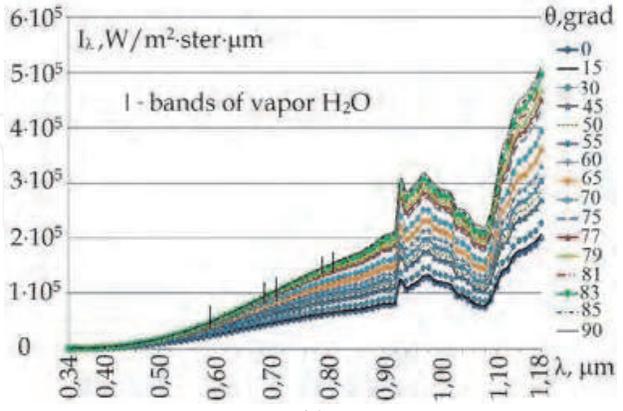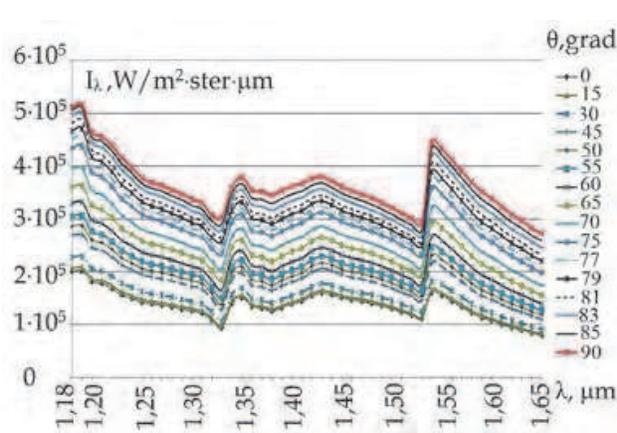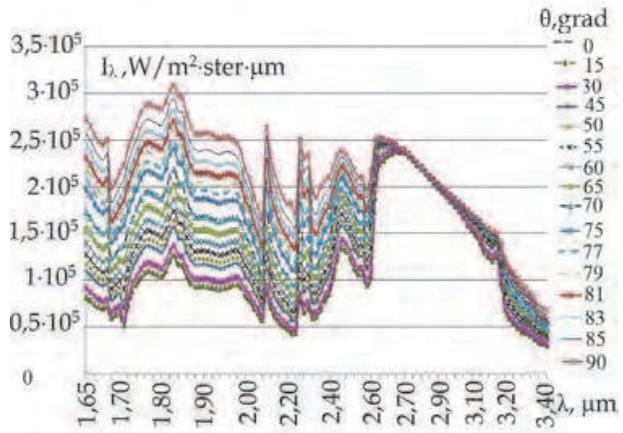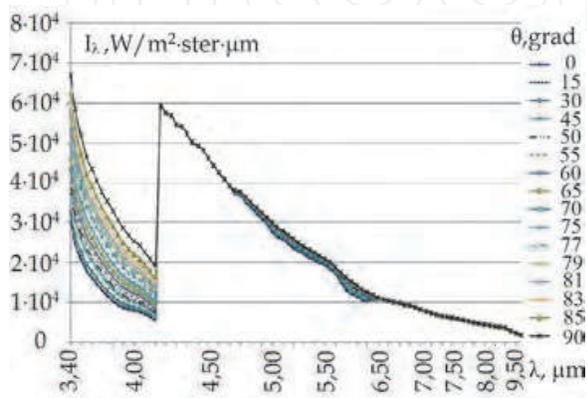
A-e)

B-a)

B-b)

B-c)

B-d)

B-e)

C-a)

C-b)

C-c)

C-d)

C-e)
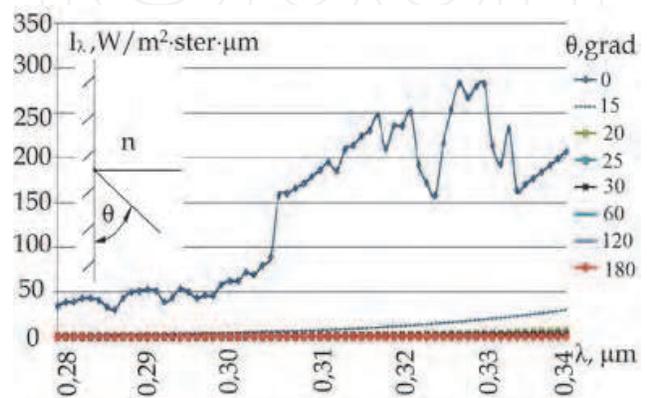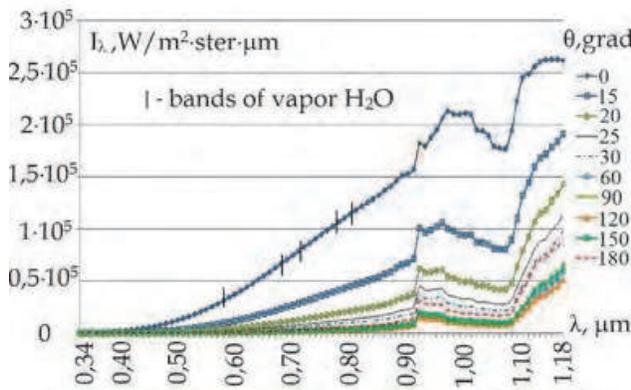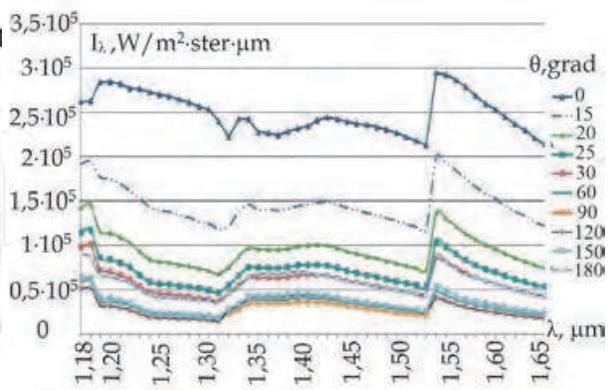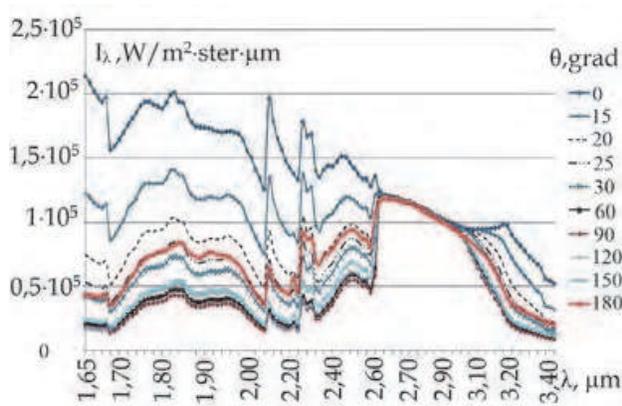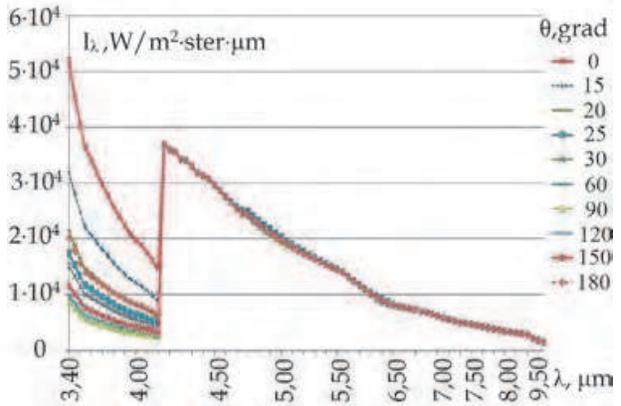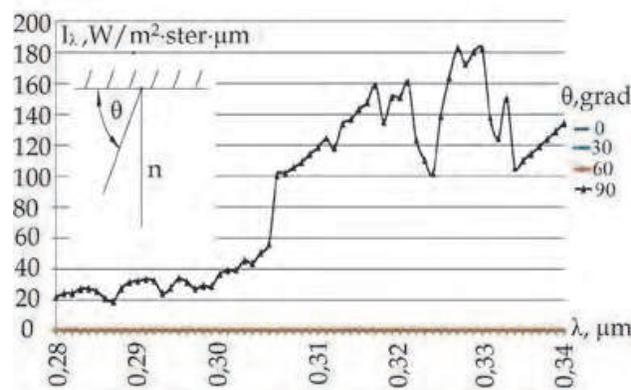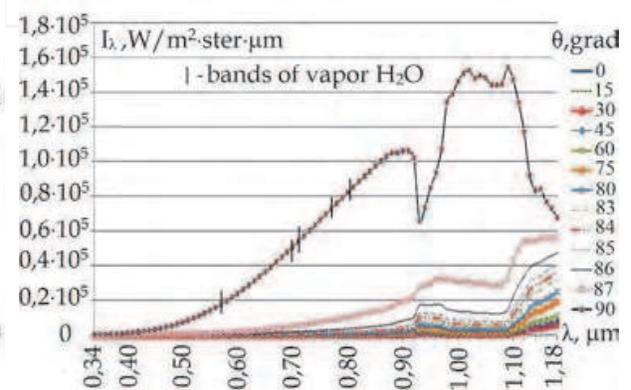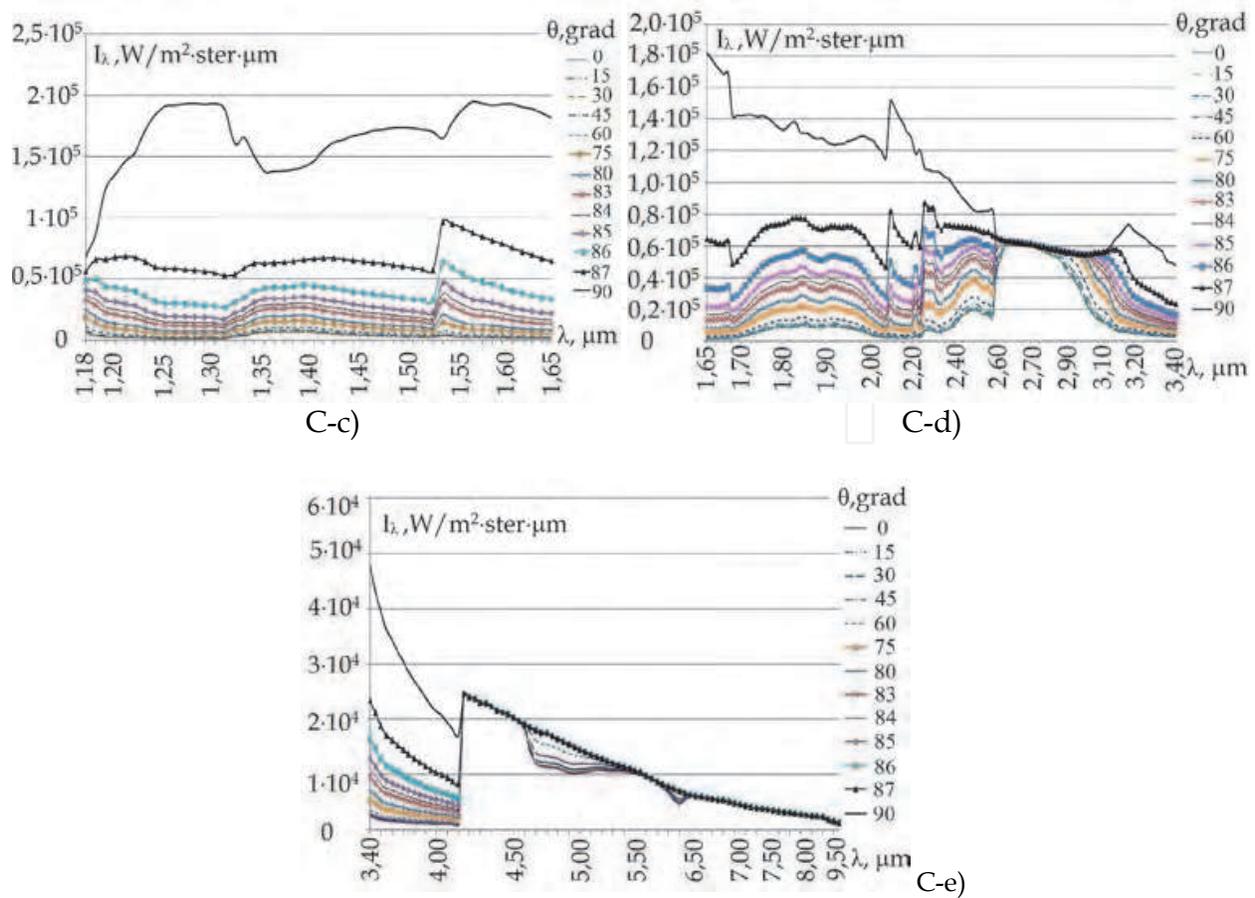
Fig. 25. Spectral and spatial distribution of thermal radiation in spectrum ranges: a) 0,28÷0,34 µm; b) 0,34÷1,18 µm; c)1,18÷1,65 µm; d) 1,65÷3,4 µm; e)3,4÷9,5 µm. A − descending radiation on a hearth heatsuscebility surface, B − falling radiation on lateral screens of a cell of a multichamber fire chamber at level 7 meter from a cut of capillaries multirow torches, C − ascending radiation at level of 18 meter from a cut of capillaries multirow torches of a cell of a multichamber fire chamber
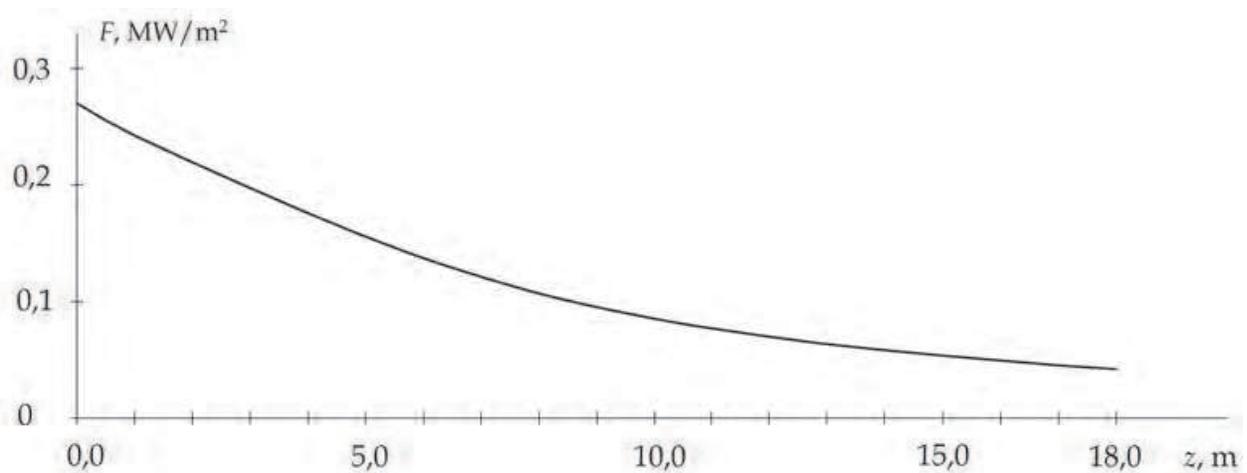
Fig. 26. Distribution of an integrated stream of the radiation depending on height of a fire chamber in case of weak approximation.
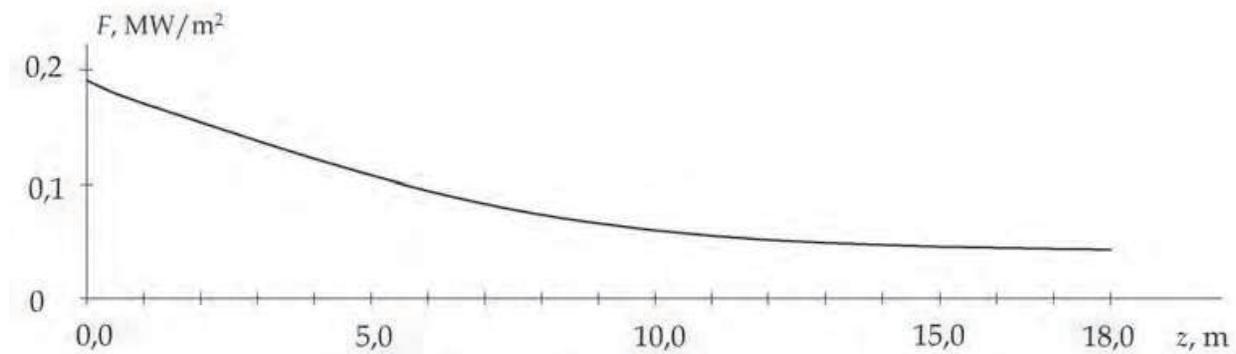
Fig. 27. Distribution of an integrated stream of the radiation depending on height the fire chambers calculated with use of function spectral transmission on a two-parametrical method of equivalent mass.
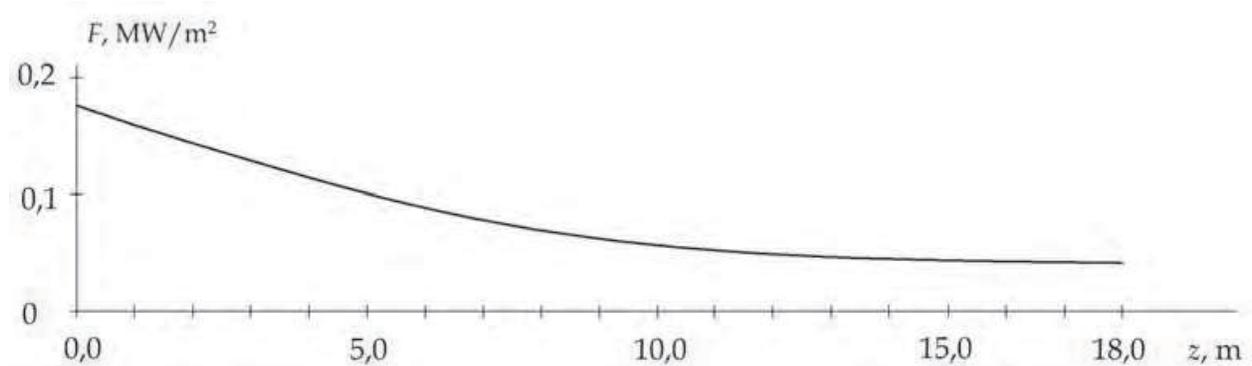
Fig. 28. Distribution of an integrated stream of the radiation calculated without effective pressure.

effective pressure in functions spectral transmission gas components underestimates radiating heat exchange on 5-6 %. The disperse phase of products of combustion influences radiating heat exchange at the expense of radiation ashes. Radiation scattering ashes poorly influences radiating heat exchange in strongly absorbing top internal atmosphere. Reflection of radiation from walls of the top internal chamber leads to reduction of speed radiating cooling in top internal volume.

Generally at heat exchange calculations it is necessary to consider the transfer over of heat at the expense of recirculation of products of combustion in a fire chamber and massexchange owing to diffusion which influence temperature distribution on volume of the chamber of combustion. With the advent of supercomputers there is possible an application of numerical methods of the decision of problems of the transfer over of radiation (Marchuk & Lebedev, 1981; Surgikov, 2004; Moskalenko et al., 1984) which restrain insufficient reliability of data on parameters of spectral lines of gas components of products of combustion.

6. Conclusion

In the conclusion we will stop on the basic results received in the course of the present work.
1. The developed measuring optic-electronic complexes for research of optical characteristics of high-temperature mediums and flames have allowed to spend registration of spectra of absorption and spectra of radiation various flames with the average and high spectral

permission at various lengths of an optical way from 0,2 to 16 m. Uniformity of temperature flames provided possibility of measurement of their temperature by optical methods with a margin error ±2 %. The method of definition nonequilibrium radiating cooling a flame from experimental data on its temperature is developed. Data on a role of nonequilibrium processes on radiating cooling optically the thin torch are received, allowing estimating influence of nonequilibrium processes of radiation in ultra-violet, visible and infra-red parts of a spectrum on radiating heat exchange of torches of aerocarriers and in top internal chambers.

2. The analysis of results of long-term measurements of radiating characteristics of gas and disperse phases of products of combustion is made and radiating characteristics various optically active components of products of combustion, including the cores (vapor H_2O and CO_2) and small components are received. Data on a microstructure sooty ashes and to its optical characteristics are received at burning of various gas hydrocarbonic components in oxygen and in air. Strong dependence of a microstructure sooty ashes from molecular structure of gas fuel and a burning mode is observed. Mass concentration sooty ashes is minimum at burning of methane CH_4 and is maximum at burning of acetylene C_2H_2. The microstructure sooty ashes at black oil burning is close to its microstructure at acetylene burning. Parameterization of gas components of products of combustion is executed on a two-parametrical method of equivalent mass.

3. The method of modeling of the transfer over of thermal radiation in nonequilibrium to radiating multicomponent non-uniform atmosphere under structural characteristics of top internal space is developed. The design of multichamber fire chambers with ascending movement of products of combustion in a fire chamber and vertical development of a flame of the hearth multirow torches forming uniform for all chambers of a multichamber fire chamber burning device of matrix type with the general gas collector for giving of gas fuel and a collector for giving of an oxidizer (air or oxygen) is offered. The burning device is expedient for the transfer out with a radiator for cooling by its water on an independent circulating contour. The design of a multichamber fire chamber at use of gas fuel allows to raise efficiency on 2-3 % and to increase it vapor-productivity in 2-3 times at preservation of parameters of vapor and boiler dimensions.

4. The closed modeling of radiating heat exchange in the chamber of combustion of a multichamber fire chamber with horizontal section of a cell of a boiler 1,25x1,6 m and 1,4x1,4 m is executed at factor of surplus of air α =1,03 and average initial speed of a current of products of combustion of 25 m/s and 20 m/s. Data in the speeds radiating cooling $\partial T(z)/\partial t, \partial T(z)/\partial z$ and to temperature profile $T(z)$ depending on height z over cuts of capillaries matrix burning devices are received. Calculations heat susceptibility on heatsusceptibility to surfaces of the top internal chamber is executed. Full stream F of thermal radiation on a fire chamber surface will be coordinated with change enthalpy on an exit from the top internal chamber with a margin error 0,3%. Nonequilibrium radiating cooling makes 7,5 %. The account of effective pressure in a fire chamber leads to growth of a full stream of radiation F on 5÷6 %.

5. Consideration of optical properties of gas and disperse phases of products of combustion hydrocarbonic fuels and the offered algorithms of numerical modeling allows to draw following conclusions:

- nonequilibrium radiation reduces concentration of harmful component NO_x;
- nonequilibrium radiation leads to heating of particles of fuel and accelerates their ignition by that more intensively, than more small particles and then more their section of absorption of radiation;

- in case of burning of gas fuel nonequilibrium radiation practically isn't transformed by products of combustion and without easing is absorbed by walls of the chamber of combustion (screens);
- in case of presence of a disperse phase nonequilibrium radiation is absorbed by aerosols (soot and fuel particles) and its role in processes of radiating heat exchange is weakened, as energy of nonequilibrium radiation as a result of absorption passes in thermal energy of particles;
- nonequilibrium radiation (especially rigid ultra-violet radiation) can to initiate photochemical reactions in processes of combustion and to influence radiating heat exchange through changes of radiating properties of products of combustion.

6. The basic component defining nonequilibrium radiation in flames is hydroxyl OH. Factors of absorption OH in ultra-violet and infra-red areas of a spectrum are defined. Quantum-mechanical consideration of formation of spectra of nonequilibrium radiation shows that nonequilibrium radiation is shown both in electronic, and in vibrational-rotary spectra of molecules OH which is in raised and basic electronic conditions: bands v_1, $2v_1$, $3v_1$, where v_1 – frequency of normal vibration. Nonequilibrium radiation OH is revealed in a vicinity of lengths of waves 1; 1,43; 2,1; 2,7; 4,1 µm in flame hydrogen-oxygen. The method of definition of vibrational temperature in radiation spectra flames is developed. Presence of spectral structure of vibrational temperature testifies to its dependence on vibrational and rotary quantum numbers.

7. For a homogeneous mediums the law of Kirchhoff is carried out. In non-uniform medium on structure it is broken also function spectral transmission becomes depending as from thin structure of a spectrum of the radiating volume, and thin structure of a spectrum of the absorbing medium, and differs from function spectral transmission for sources of not selective radiation which are measured in laboratory experimental researches. The transfer over of selective radiation is influenced by following factors: the temperature self-reference of spectral lines of radiation, displacement of spectral lines with pressure, the temperature displacement of the spectral lines which have been found out for easy molecules (vapor H_2O, CH_4, NH_3, OH). Till now influence of last two factors wasn't investigated. Quantummechanics calculations of displacement of spectral lines with pressure make thousand shares of cm^{-1} and in conditions turbulized atmosphere can't render essential influence on function spectral transmision. Temperature displacement of spectral lines in a flame make the 100-th shares of cm^{-1} and at high temperatures reach semiwidth of spectral lines and more. It leads to that radiation of a high-temperature kernel of a torch is weakened to a lesser degree by its peripheral layers that increases heatsusceptibility surfaces of heating at the expense of radiating heat exchange. At registration of radiation of a torch of the aerocarrier in atmosphere the effect of an enlightenment of atmosphere in comparison with the account only the temperature self-reference of spectral lines of radiation of a torch is observed more considerably.

8. The analysis of radiating heat exchange between gas and disperse phases of products of combustion gaseous fuels shows that the temperature sooty particles should be below thermodynamic temperature of gases that weakens influence of a disperse phase on radiating heat exchange in the top internal chamber. On the other hand, absorbing properties of sooty ashes define its role in radiating heat exchange, forming a field of thermal radiation in space of the top internal chamber. Scattering of radiation by particles of a disperse phase of products of combustion shows weak influence on distribution of streams of radiation on heatsusceptibility surfaces of the top internal chamber. Mass concentration of

sooty ashes and its microstructure considerably depend on structure of gas fuel and a burning mode. At performance of calculations of radiating heat exchange the disperse phase of products of combustion is supposed multicomponent and is defined by various mechanisms of its formation. Each fraction of an aerosol has the optical characteristics, normalized on easing factor at length of a wave λ =0,55 µm. Spectral factors of easing, absorption, scattering and indicatryss of scattering are calculated for polydisperse ensemble of spherical particles of the set chemical compound. The electronic database includes three fractions of sooty ashes (primary thin-dispersion sooty ash, fraction of average dispersion, and coagulation fraction of soot of smoke gases), flying fraction ashes and roughly-dispersion fraction of products of combustion of firm fuel. As structural characteristics optical density on length of a wave λ =0,55 µm for various fractions of a disperse phase of products of combustion acts. The real spectral optical characteristics entering into settlement formulas are calculated on an electronic database in the assumption that burning of each component of fuel occurs independently that allows using optical density and a microstructure of sooty ashes by results of measurements on ardent measuring complexes.

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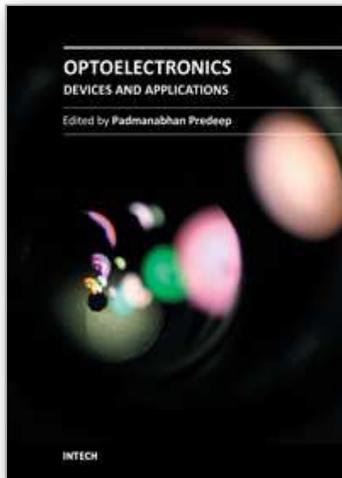
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