ANALYSIS OF IR RADIATION OF TURBULENT FLUXES OF MOLECULAR GASES

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An approximate method is proposed for the analysis of IR radiation for turbulent jets of molecular gases, which is based on utilizing a model probability distribution function for the temperature and concentration.

The fluctuation characteristics of the temperature and concentration of radiating components around the mean values in turbulent jets and wakes depend on the mixing rates to the molecular level. The delay in the mixing of heated molecular gases issuing from a nozzle should be taken into account, for instance, in analyzing the optical characteristics of turtical jets. The instantaneous concentrations in axisymmetric jets were measured in [1] by means of the scattered light radiation. The results obtained indicate that unmixed volumes of gas flowing out of the nozzle penetrate to the outer edge of the jet in the form of narrow bands or shallow spots. Such a structure of the concentration field is associated with the jet mixing mechanism which is due to rupture of the vortex rings and results in circumferential ejections of the whirling gas from the central part of the stream. The presence of finite volumes of unmixed hot gas on the jet edge can evidently turn out to be the decisive factor in estimates of the transverse jet dimensions according to thermal radiation or in analyses of brightness temperature fields in circumferential zones of the jet.

In cases of practical interest, the fluctuations due to the delay in mixing of the gas issuing from the nozzle are optically fine ($\varkappa L \ll 1$) in the IR spectrum range. In this case correlation of the radiation intensity fluctuations and the absorption coefficient can be neglected and the mean radiation intensity is determined by the equation

$$\frac{d\langle I\rangle}{dl} = \langle \varkappa B\rangle - \langle \varkappa\rangle \langle I\rangle, \tag{1}$$

Taking account of optically fine fluctuations therefore reduces to local averaging of the optical characteristics of the medium in the expression for the radiation intensity. A single-point probability distribution function for the thermodynamic parameters is required for taking such an average. The method of constructing the approximate temperature and concentration probability distribution functions for taking account of the mixing delay is proposed in [3]. Its crux is modeling of all possible states of a volume element of the turbulent medium in the form of a superposition of three constituents: the gas of the external medium (atmosphere) and the working gas of the jet, which retains its properties completely, and also the homogeneous mixture of these two constituents. Appropriate quantitative relations were obtained within the framework of a "kε2" model of turbulence [4]. This method is actually equivalent to a representation of the temperature and concentration probability distribution functions in the form of the sum of a finite number of δ-functions. Such a representation of the distribution function was first proposed by Donaldson for the analysis of chemical reactions [5]. The Donaldson method has not been utilized extensively for reacting systems because of the complexity of its realization. However, it can turn out to be quite fruitful in an analysis of the radiation in turbulent nonreacting flows.

The method considered for modeling the temperature and concentration fluctuations was used in [3] for numerical investigations of radiating turbulent jets. It was assumed in [3] that the optical properties of the medium can be described by the absorption coefficient averaged over a small spectrum range. The method proposed for taking account of turbulent fluctuations will be used in this paper to analyze the IR radiation of molecular gases, where the insertion of the absorption coefficient averaged with respect to the frequency is not generally allowable.

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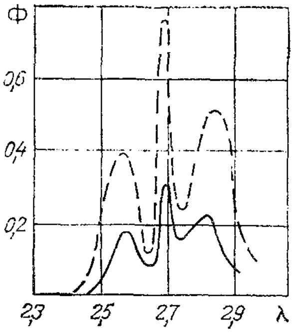

Fig. 1

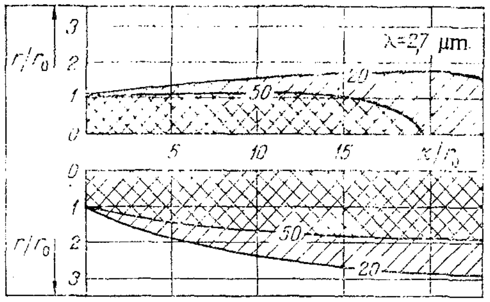

Fig. 2

Fig. 1. Spectrum distribution of radiation flux normal to the axis from a circular jet section. Distance from nozzle exit $x = 10r_0$. Computations were performed over average T and C (solid lines) and with a model of taking account of the mixing delay (dashes); λ, μm; Φ, W/sr·cm·μm.

Fig. 2. Isotherms of the excess of the brightness temperatures over the background in a computation by means of average T and C (upper half of the figure) and with a model of taking account of the mixing delay (lower half).

Absorption of radiation in the IR band occurs in molecular gases in the vibrational–rotational bands outside of whose limits the gases are practically transparent. The vibrational–rotational band is a set of individual spectrum lines for whose characteristics the position, intensity and form of the contour must be given. The intensity spectral distribution in the band can be obtained in principle, by using the equation of monochromatic radiation transport. To do this, all the lines within the band must be taken into account in the analysis. The fundamental problems occurring in such an approach are related to boundedness of the information about the individual spectrum lines and to extremely large calculational expenditures. An alternative approach is utilization of models of the bands that approximate the properties of the actual apectrum averaged over a small spectrum band of 10-50 cm^{-1}.

The most widespread method associated with utilization of band models is the Curtis–Hodson method, which we shall henceforth use as basis. It should here be noted that the proposed method of taking account of the mixing delay is sufficiently universal and can also be used in combination with other methods of analyzing the radiation.

The radiation intensity at a point a distance z from the beginning of the beam is determined by the expression

$$I(0) = \int_0^z B(l) \frac{\partial}{\partial l} [1 - \tau(l)]\, dl. \tag{2}$$

The problem of computing the transmittance $\tau = \int_{\Delta\omega} d\omega [1 - \exp(-\int_0^l \varkappa dl')]$ in the Curtis–Hodson method is solved by replacing the transmittance of an inhomogeneous layer by the transmittance of a hypothetical homogeneous layer with appropriately selected parameters. Within the framework of such an approach, by using the model of a Goode band (a random model with exponential distribution of the lines of force), the following relationship can be obtained [6]:

$$\tau(l) = \exp\left\{-\left(\frac{s_E}{d_E}\right) u \left[1 + \frac{(s_E/d_E)}{4(\gamma_E/d_E)}\right]^{-1/2}\right\}, \tag{3}$$

where

$$u = \int_0^l \rho dl'; \quad (s_E/d_E) = \int_0^l (s/d)\, \rho dl'/u;$$

$$(\gamma_E/d_E) = \int_0^l (s/d)(\gamma/d)\, \rho dl' / \int_0^l (s/d)\, \rho dl'.$$

Writing the derivative $\partial\tau/\partial l$ out explicitly and using the approximate equality

$$\int_0^l \varphi dl' = \int_0^l \langle \varphi \rangle dl', \tag{4}$$

for averaging the integrals in (3) with respect to the turbulent fluctuations, we obtain an expression for the means with respect to the space–time inhomogeneities and the small radiation intensity spectrum band*

$$\langle I \rangle = \int_0^z \exp\{-\langle A_1 \rangle \langle A_3 \rangle\} \left\{ \langle A_1'B \rangle \langle A_3 \rangle - \frac{\langle A_1 \rangle^2}{\langle A_3 \rangle} \frac{2\langle A_2 \rangle \langle A_1'B \rangle - \langle A_1 \rangle \langle A_2'B \rangle}{8 \langle A_2 \rangle^2} \right\} dl, \tag{5}$$

where

$$\langle A_1 \rangle = \int_0^l \langle (s/d)\rho \rangle \, dl'; \ \langle A_2 \rangle = \int_0^l \langle (s/d)(\gamma/d)\rho \rangle \, dl'; \ \langle A_3 \rangle = \left(1 + \frac{\langle A_1 \rangle^2}{4\langle A_2 \rangle}\right)^{-1/2};$$

$$\langle A_1'B \rangle = \langle B(s/d)\rho \rangle; \ \langle A_2'B \rangle = \langle B(s/d)(\gamma/d)\rho \rangle.$$

Relationship (4) can be used in deriving (5) when 1) the optical thickness corresponding to the segment of integration from 0 to l is much greater than the optical thicknesses of the fluctuations being realized in this segment and 2) the scales in which the mean values of the temperature and concentration undergo substantial changes exceed the correlation lengths of the fluctuations in the corresponding quantities by several times at least. For beams passing through the circumferential zones of the jet, these conditions are sufficiently natural, where the former actually corresponds to the approximation of optically thin fluctuations within whose framework (1) was obtained.

Separate results of numerical investigations of the influence of the mixing delay on the radiation are presented in Figs. 1 and 2. They were obtained by using (5) and the methodology in [3]. Computations were performed for a submerged jet with initial temperature T_0 = 700°K, initial velocity u_0 = 100 m/sec, and molecular weight of the working mixture 28 g/mole. The temperature of the ambient air was assumed at 288°K. The radiation of the jet was determined by the presence of water vapor therein (1% by mass in the working mixture). The H_2O content in the external medium was neglected. The nozzle radius is 10 cm and the total pressure is 1 atm.

The spectrum distribution of the radiation flux from a circular section of the jet is represented in Fig. 1 for the 2.7-μm band. As is seen, the presence of unmixed hot gas plays an important part in the formation of the jet radiation spectrum. The necessity of taking account of the mixing delay in estimates of the transverse jet dimensions by means of the thermal radiation is shown in Fig. 2, where the computed isotherms of the brightness temperature excess over the background are presented.

The elucidated methodology for taking account of the mixing delay to the molecular level can be utilized successfully for engineering computations of the radiation since besides the sufficiently correct description of the turbulent mixing singularities it does not result in a significant increase in the amount of calculations.

NOTATION

I, radiation intensity; $\varkappa$, absorption coefficient; B, Planck function; l, distance measured along the beam; L, dimension of the spatial perturbation related to the turbulence; τ, transmittance; ω, frequency; T, temperature; C, mass concentration; ρ, density; s, γ, d, lines of force, line half-width, and spacing between lines averaged over the spectrum band; λ, wavelength; T_0, u_0, r_0, temperature, velocity, and radius of the jet in the initial section; and <> signifies averaging over the turbulent fluctuations.

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*Kabashnikov and Kmit [7] obtained an analogous result earlier.

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INTENSIFICATION OF HEAT EXCHANGE WITH SURFACE BOILING OF WATER IN PIPES WITH ANNULAR TURBULIZER

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The article demonstrates the possibility of greatly intensifying heat exchange with surface boiling of water moving in pipes with annular diaphragm.

Reducing the weight and dimensions of evaporative heat exchange apparatus used in the chemical and food industry and other fields of engineering is an important scientific and technical as well as an economic problem. One of the most promising ways of solving this problem is intensification of heat exchange by artificial turbulization of the flow.

In many evaporative apparatuses the heating medium is condensing steam, and inside the pipes surface boiling takes place. The practical realization of most of the known methods of intensifying heat exchange in these apparatuses is prevented because there is no technology for the mass production of the investigated heat exchange surfaces, because it is necessary to work out a special technology of assembling heat exchange apparatuses consisting of these surfaces, because of the relatively low efficiency, and because of the lack of simultaneous intensification of heat exchange outside and inside the pipes.

At the Moscow Aviation Institute a method of intensifying heat exchange in tubular heat exchange apparatuses was worked out, and the efficiency of the method was tested in pipes, annular channels, and longitudinally washed bundles of pipes with gas and liquid flow [1]. The essence of the method consists in producing evenly spaced annular grooves (by rolling) on the outer surface of pipes (Fig. 1). These grooves and the annular diaphragms with smooth configuration forming on the inner surface of the pipes turbulize the flow in the near-wall layer and intensify heat exchange outside and inside the pipe. Yet the outer diameter of the pipes is thereby not increased, and this makes it possible to leave the existing technology of assembling tubular heat exchangers unchanged. Such pipes are also fairly free of pollution and salt deposition. Production of the pipes with rolled grooves is carried out on standard equipment.

Investigations [2] showed that with film condensation on the outer surface of vertical pipes, the annular grooves increase the heat transfer coefficient by a factor of 1.7-2.8. The object of the present work is to study the possbility of intensifying heat exchange by the method in question when there is surface boiling of a liquid in pipes.

The experimental section (Fig. 1) was a vertical single-pipe evaporator 1. Experiments were carried out with the boiling of water heated to 95-97°C in tank 6. Water circulation was ensured by pump 5. The water-steam mixture from the evaporator was fed to the separator 9 where the steam was separated from the liquid. The liquid was returned to tank 6, and the steam was pumped by the vacuum pump via condenser 8 into the measuring vessel 4. The water flow rate at the inlet to the experimental section was measured by the rotameter 3.

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