HEAT AND MASS EXCHANGE IN AN OPTICALLY THIN, TURBULENT BOUNDARY LAYER IN AN IR RADIATION FIELD

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The procedure and results of an experimental investigation of the temperature and velocity distribution in a plane, incompressible, turbulent boundary layer of air and of CO_2 in an IR radiation field are presented. Data are given on heat exchange under the conditions of curtain cooling.

I. Statement of the Problem

The flow of optically active media in an IR radiation field for systems with different geometrical configurations is accompanied, as shown by the results of theoretical and experimental research, by interconnected processes of transfer of thermal energy by the mechanisms of conduction, convection, and thermal radiation [1-20]. General aspects of this problem have been discussed in [5], as well as in [14]. One of the important problems of radiative gasdynamics is the investigation of the mutual influence of conduction, convection, and thermal radiation in optically active, turbulent boundary layers and the action of radiation on turbulence [6, 21]. This problem was first solved experimentally in [17-19].

Two tasks are set in the present experimental work: 1) to isolate in practically pure form the influence of an external flux of IR radiation on the temperature and velocity distributions in a turbulent boundary layer of CO_2, including the region of the sublayer of molecular heat conduction (the laminar thermal sublayer); 2) to investigate radiative–convective heat exchange under the conditions of a tangential curtain and porous injection into the boundary layer on a plane surface over which flow occurs in an IR radiation field.

The choice of an incompressible, optically active, turbulent boundary layer as the research subject is connected both with its practical importance and with the significant fact that the presence over the height of the layer of regions with fundamentally different structures of turbulence (a viscous and thermal sublayer, a buffer zone, a turbulent core, and an overlayer with intermittent effects) and with corresponding optical depths allows one to study the interaction of conduction, convection, and thermal radiation in the zones of generation, transfer, and dissipation of turbulent kinetic energy. The peculiarities of the processes of generation of wall turbulence and of its structure in the boundary layer were investigated in [22, 23]. A survey of turbulence models and a discussion of questions of the influence of thermal radiation on turbulence are presented in [6, 21]. In accordance with the foregoing, in the study of the action of an external flux of IR radiation on the temperature and velocity distributions in a turbulent boundary layer much attention is paid to measurements in the vicinity of the surface over which the flow occurs, especially in the laminar thermal sublayer.

II. Measurement Procedure, Metrological Characteristics of Sensors, and Velocity and Temperature Profiles in a Turbulent Boundary Layer of Air in an IR Radiation Field

A subsonic aerophysical installation of the closed type, equipped with a measurement system and a source of IR radiation [18], was created for the solution of the stated problems. The measurement section consisted of a nozzle, the calibrated cut of which had a height of 0.032 m and a width of 0.132 m, and a channel formed by side walls with a height of 0.180 m and six plates with a length of 0.09 m and a width of 0.132 m located in its lower part. The

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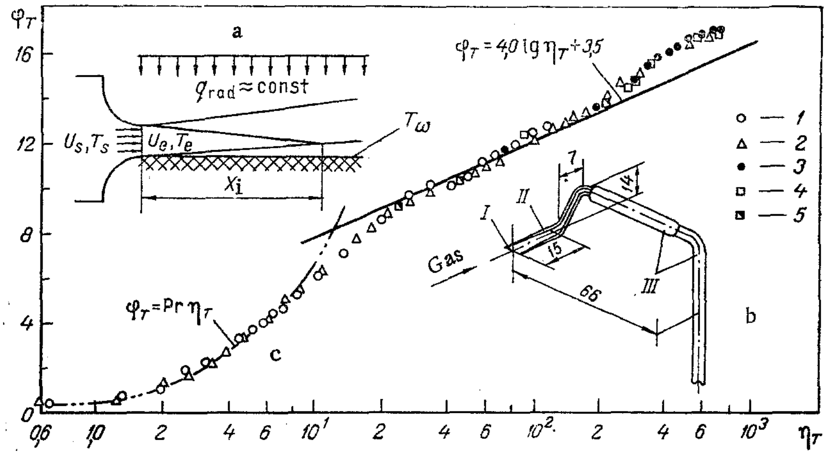


Fig. 1. Temperature distribution in a turbulent boundary layer of air for $q_w \neq 0$ in the presence of IR radiation and in its absence for the conditions $T_w/T_e \approx$ idem, $Re_x \approx$ idem, and $r_w \approx 0.95$: a) flow scheme; b) resistance microthermometer: I) gold-plated tungsten filament, d_f = 20 μm; II) manganin electrodes; III) holder; c) temperature profile: 1, 3, 4) $q_{rad} \neq 0$; 2, 5) q_{rad} = 0; $q_w \neq 0$.

ratio of the area of the forechamber of the nozzle to the area of its cut was 20. The jet, upon escaping from the nozzle, propagated along the six plates (Fig. 1a). The Reynolds number at the nozzle cut was $Re_s = (2.5-4)\cdot10^4$. In [24] it was shown that for $Re_s = 7\cdot10^3-6\cdot10^4$ the jet was turbulent. The channel was closed on top with a semicylindrical cover within which was located the source of IR radiation of the KNS-32/711 type of SiC with a diameter of 32 mm and a working section with a length of 0.54 m. The emissivity of the radiator, measured on the apparatus of [25], was $\varepsilon_R \approx 0.97$ and depended little on wavelength. The coefficient of reflectivity of the six working plates and the inner brass screens of the channel was $r_w \approx 0.95$, which was achieved by nickel plating and polishing them. The nonuniformity of temperature and velocity over the area of the nozzle cut did not exceed 2%. The gas temperature at the exit from the nozzle could be varied within wide limits using an electric heater and regulator of the RNO-10 type. The temperature of the IR radiation source was regulated smoothly with an ROT-25 transformer.

The six mirror plates were located on a common asbestos cement slab 22 mm thick, additionally insulated on the outside by a layer of foam plastic 50 mm thick. Ribbon electric heaters, the circuits of which included an ST-5000 voltage stabilizer and an I-512 current transformer, were mounted below each of the plates through a thin layer of asbestos cement to run the tests under the conditions of heat exchange in the absence of IR radiation. Nichrome–constantan thermocouples with an electrode diameter of 0.2 mm, led out from the embedding sites along isothermal lines, were embedded every 15 mm along the length of the working plates. The thermocouples were calibrated to within 0.1°C in constant-temperature baths.

We developed a resistance microthermometer, a combined temperature and velocity sensor, and a positioner based on a micrometer, permitting movement of the sensors with a step of 10 μm. A general view of the resistance microthermometer is presented in Fig. 1b. Filaments of gold-plated tungsten with thicknesses of 3, 8, and 20 μm were welded, on a special stand under a microscope, to polished manganin electrodes sharpened to points. All the main measurements were made with the 20-μm sensing element. The current through the gold-plated filament was $1.3\cdot10^{-3}$ A. The sensor holder had a mirror surface. Calibration of the sensor from 273 to 400°K showed that the temperature dependence of its resistance was linear. The combined sensor, which had a practically mirror surface, contained probes for measuring the total and static pressures in the boundary layer, as well as a Nichrome–constantan thermocouple shielded inside a tube with air flow. Problems of measurements of the temperature of a gas stream using thermocouples and their shielding from radiation were discussed in [26], while those for a resistance thermometer were discussed in [27]. The peculiarities of velocity measurements with Pitot tubes are presented, e.g., in [28].

The following measurements were provided for: 1) the temperature in the turbulent boundary layer, with the resistance microthermometer; a standard resistance coil of type R-321, an M195/1 galvanometer, and a potentiometer of type R306 of class 0.002 were used in the circuit; 2) the temperature and velocity in the boundary layer and at the nozzle cut using combined sensors, as well as the temperatures of the six plates using thermocouples; the thermo-emf was measured with a semiautomatic potentiometer of type R2/1 of class 0.015; 3) the temperature along the length of the source of IR radiation of type KNS 32/711 with an OPPIR-017 optical pyrometer through optical windows in the semicylindrical cover; the temperature nonuniformity along the length of the radiator did not exceed 2%; 4) the electric load applied to the heaters of the six plates using a wattmeter of type D-57 of class 0.1; 5) the temperatures of the outer housing of the measurement section, the asbestos cement slab, and the ambient air near the foam plastic thermal insulation to allow for heat losses based on preliminarily obtained calibration data; 6) the CO_2 concentration at the nozzle cut using an analyzer of type VTI-2; 7) the flow rates of air and CO_2 supplied for tangential and porous injection with rotameters of type RS-7 specially calibrated.

To isolate in practically pure form the effects due to the interaction of the external flux of IR radiation with the optically active, turbulent boundary layer of CO_2 we observed the following conditions: 1) the boundary layer is incompressible; 2) the nonisothermicity factor is $T_w/T_e \approx 1.0$ (T_w and T_e are the temperatures of the wall and at the outer limit of the layer, respectively); 3) measurements in the boundary layer corresponded to the initial section of the wall turbulent jet, where the longitudinal pressure and temperature gradients are practically equal to zero; 4) the external source of IR radiation of the KNS-32/711 type is an almost absolutely black body at $T_R \geq 1200°K$ ($\varepsilon_R \approx 0.97$); 5) the reflectivity of the six plates over which the flow occurred was $r_w \approx 0.95$ according to measurements of the Institute of Thermophysics, Siberian Branch, Academy of Sciences of the USSR and, as follows from [29], depended little on the wavelength up to 400°K; 6) measurements using the resistance microthermometer and combined sensor developed were made with practically no distortions in the IR radiation field.

In accordance with the experimental data of [30], when a turbulent jet flows out of a nozzle along a plane surface a boundary layer forms on it. Measurements of the temperatures and velocities in the semibounded jet showed that the length of its initial section was $X_i/S \leq 10$, i.e., for a nozzle cut with a height S = 32 mm the length is $X_i \leq 0.32$ m. The experimental data on heat exchange without radiation within the initial section of the jet were described with an error of $\leq$10% by the dependence for a turbulent boundary layer at a flat plate in the form $St=f(Re_T^{**m}, Pr^n)$, where Re^{**}_T is the Reynolds number with respect to the energy-loss thickness; St and Pr are the Stanton and Prandtl numbers; m = 0.25; n = 0.75 [31]. The velocity and temperature profiles without radiation measured in the cross section X = 0.2 m with the combined sensor satisfied the standard power-law functions for a turbulent boundary layer [31]. Later all the main measurements in the IR radiation field were made in the cross section at X = 0.2 m.

The experiments using the resistance microthermometer (Fig. 1b) are the most important in the methodological respect for the solution of the stated problems. In Fig. 1c we present the temperature distribution over the height of the turbulent boundary layer, including the laminar thermal sublayer, in universal coordinates for X = 0.2 m, both in the IR radiation field and in its absence, under the conditions $Re_S \approx$ idem, $Re_X \approx$ idem, and $T_w/T_e \approx$ idem. Here $Re_X = 0.35 \cdot 10^6$, $T_w = 383°K$, and $T_e = 328°K$. The degree of turbulence in a semibounded jet is very high [24, 30], which facilitated the formation of a developed turbulent boundary layer. In the absence of radiation the heat flux q_w = const at the wall ($T_w > T_e$) was created by electric heaters, while in the presence of an IR radiation field it was created through absorption by the plates ($r_w \approx 0.95$) of a small part of the radiation initiated by the source at the temperature $T_R = 1273°K$. All the measurements of air temperature were made from the wall. The step in the vicinity of the wall was 10 μm. The condition that the sensor filament be parallel to the plate was satisfied. The minimum distance of the center of the gold-plated filament from the wall was $\leq$15 μm, while the corresponding value of the universal vertical coordinate $\eta_T \approx 0.6$ was monitored before the tests using a KM-6 cathetometer, by the electrical contact, and by matching the filament with its reflection in the mirror plate. At $y \leq 15$ μm the air temperature measured by the resistance thermometer differed by no more than 1.5% from the wall temperature measured at X = 0.2 m by a thermocouple. The temperature distribution in the thermal sublayer in the radiation field and in its absence was described by

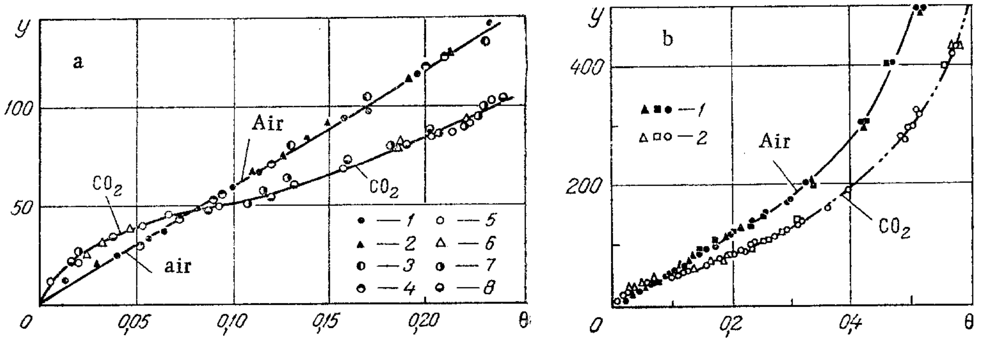


Fig. 2. Distributions of temperature θ in air and CO_2 in the vicinity of a plate with $r_w \approx 0.95$ in an IR radiation field under the conditions $T_w/T_e \approx$ idem and $Re_x \approx$ idem: a) laminar thermal sublayer, $\delta_1 \approx 130$ μm: 1-4) air, $q_{rad} \neq 0$; 5-8) CO_2, $q_{rad} \neq 0$; b) laminar sublayer and buffer zone: 1) air, $q_{rad} \neq 0$; 2) CO_2, $q_{rad} \neq 0$, $\theta = (T_w - T)/(T_w - T_e)$; y, μm.

the linear function $\varphi_T = \eta_T \Pr$ (Fig. 1c). Here, $\varphi_T = \frac{(T_w - T)/(T_w - T_e)}{\sqrt{St}} \Pr^{0.3}$; $\eta_T = \frac{yU_e \sqrt{St} \Pr^{0.3}}{\nu}$; y is the vertical coordinate; U_e is the velocity at the outer limit of the layer; T is the thermodynamic air temperature. The thickness of the sublayer was ~130 μm while $\eta_{T,1} \approx 11.7$. In the region of the turbulent core the temperature variation corresponded to the function $\varphi_T = (4.0 \lg \eta_T + 3.5)$, in which the coefficients differ from the standard coefficients in the universal function for velocity in connection with the fact that the turbulent and molecular Prandtl numbers are less than unity. The coefficients in the expression for φ_T agree with the experimental data of [32, 33]. The thickness of the thermal boundary layer is $\delta_T \approx 6$ mm. The air temperatures at the outer limit of the layer measured by the resistance thermometer and the shielded thermocouple of the combined sensor differed by 0.2% without the radiation field and by no more than 1.5% in the IR radiation field. The maximum systematic error in measurements of the air temperature by the thermometer in the radiation field as $y \to 0$ did not exceed 1-2%. Even as $U \to 0$ the Nusselt number is $Nu > 2$ for the 20-μm filament and the coefficient of heat transfer is $\alpha_i \sim 2 \cdot 10^3$ W/m². The Knudsen number for the sensor filament is $Kn \ll 1$, which corresponds to the absence of rarefaction effects in flow over the 20-μm filament.

Thus, the results obtained showed that the resistance microthermometer created and the micropositioner were a reliable instrument for temperature measurements in a turbulent boundary layer of air under the action of an intense external field of IR radiation, including all the zones of the layer. Moreover, from the measured linear temperature distribution in the sublayer the heat flux from the wall to the air was determined with an error not exceeding 5%. The measurements of velocities and temperatures with the combined sensor also showed its reliability. The results obtained then allowed us to proceed to the investigation of optically active, turbulent boundary layers.

III. Measurements of Temperature and Velocity Fields in an Optically Thin, Turbulent Boundary Layer of CO_2 in an IR Radiation Field

The presence of plates with a reflectivity $r_w \approx 0.95$ made it possible, on the one hand, to eliminate the influence of the self-emission of the boundaries on the heat exchange and, on the other, to intensify the interaction of the IR radiation and CO_2 molecules, having several absorption bands in the spectrum, through the radiation reflected from the wall. The influence of highly reflective boundaries was shown theoretically, e.g., in [3]. Carbon dioxide from tanks was supplied to the hermetic installation through a silica-gel dessicant. The CO_2 concentration at the nozzle cut did not exceed 92%. All the measurements were made upon reaching a steady thermal state in the working section. In Figs. 2-4 we present the distributions of temperature in the vicinity of the wall and of velocity and temperature in the turbulent core of the boundary layer for air and CO_2, in the presence of an external IR radiation field and in its absence, for identical flow conditions, i.e., for $Re_S \approx$ idem, $Re_X \approx$ idem, $T_w/T_e \approx$ idem, and $Bo \approx$ idem, where Bo is the Boltzmann number, in the cross section X = 0.2

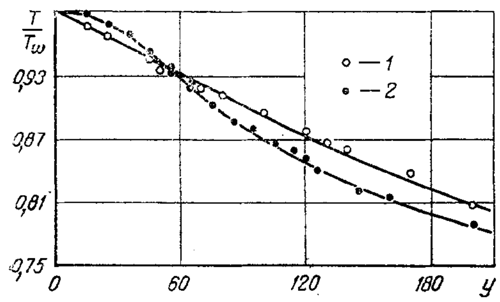


Fig. 3. Air and CO_2 temperatures as functions of the coordinate near the plate in an IR radiation field: 1) air; 2) CO_2. $T_w/T_e \approx$ idem, $Re_x \approx$ idem.

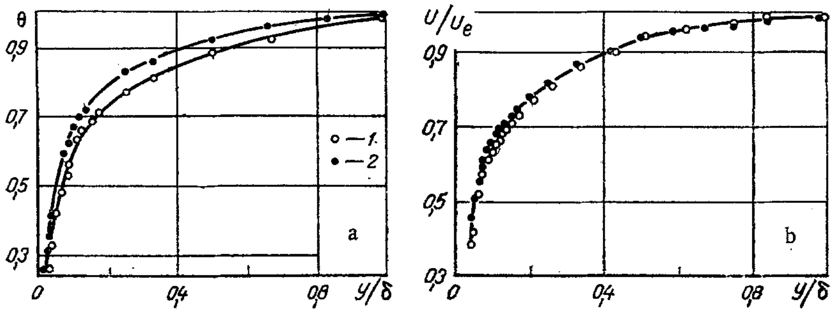


Fig. 4. Distributions of temperature and velocity in turbulent boundary layers of air and CO_2 in an IR radiation field: a) temperature profiles; b) velocity profiles: 1) air; 2) CO_2. $T_w/T_e \approx$ idem, $Re_x \approx$ idem.

m. In the tests Bo = 0.3, T_w = 383°K, and T_e = 328°K. Air and CO_2 differ in thermophysical properties and, in addition, there is the absorption of about 10% of the external radiation by the CO_2 layer with a height of about 0.18 m located between the radiation source and the boundary layer. To maintain identical flow conditions, $T_w/T_e \approx$ idem, in particular the temperature of the radiator was T_R = 1273°K in air and T_R = 1150°K in CO_2. The heat flux from the wall to the gas in the radiation field was created due to the absorption by the plates of about 5% of the incident radiation ($r_w \approx 0.95$). The measurement procedure developed enabled us to obtain the temperature distributions with a resistance microthermometer in a layer of CO_2 in an IR radiation field, including the laminar thermal sublayer and the buffer zone of the turbulent layer (Fig. 2a, b). The relative temperature difference $\theta = (T_w - T)/(T_w - T_e)$, characterizing the heat exchange in the boundary layer, determines the effects of the influence of IR radiation on the transfer of thermal energy in the CO_2 boundary layer. It is seen from Fig. 2 that in the laminar thermal sublayer the temperature profile in CO_2 in a radiation field has a nonlinear character in comparison with that for air, where the profile is linear. The nonlinearity is due to energy release in the wall layer of CO_2 at the practically mirror plate with excitation of CO_2 molecules by photons of both the external IR radiation and that reflected from the plates. Special measurements showed that the absorbing—emitting layer of CO_2 with a thickness of about 0.18 m located above the boundary layer is of considerable importance in this case. The total influence of the external radiation on the temperature field in CO_2 is manifested in the development of a peculiar source of heat release near the wall (Fig. 3). At $y < 55$ μm the temperature in the radiation field is higher in CO_2 than in air while the temperature gradient at the wall is lower in CO_2 than in air under identical flow conditions. At $y > 55$ μm it is higher, conversely, while at $y \approx 55$ μm there is a certain "equilibrium" point. The decrease in the temperature gradient at the wall in CO_2 under the influence of radiation leads to a decrease in the convective heat flux from the wall to CO_2, which results in a decrease in the internal energy and temperature of the layer at $y > 55$ μm (Figs. 2 and 3). In the vicinity of the wall the difference between θ in CO_2 and air reached 80%. The experimental data obtained in the sublayer of the turbulent boundary layer of CO_2 are in qualitative agreement with the results of theoretical work [10, 20] and are quantitatively described satisfactorily by the calculation model of [18, 34]. The measurement procedure allowed us to obtain values of the temperature at 11-12 points over the height of the sublayer, comprising about 130 μm. The deformation of the temperature profile in CO_2 under the influence of IR radiation (Fig. 2) is due to the change in the corresponding temperature gradient in the vicinity of the wall. In the zone of the boundary layer where the generation of turbulence energy equals its dissipation, the rms pulsation of temperature is $\sqrt{\langle T'^2 \rangle} \sim LE^{-1/2}\sqrt{\langle v'^2 \rangle}|d\bar{T}/dy|$, where L is the integral scale of the turbulence; E is the kinetic energy density of the turbulent pulsations; $\bar{T}$ is the average temperature; $\sqrt{\langle v'^2 \rangle}$ is the rms pulsation of the vertical velocity component. One can assume that under the experimental conditions the quantity $LE^{-1/2}\sqrt{\langle v'^2 \rangle}$ will be the same in CO_2 and in air in the radiation field. But since $|d\bar{T}/dy|_{CO_2} \neq |d\bar{T}/dy|_{air}$, in the radiation field the temperature pulsation $\sqrt{\langle T'^2 \rangle}$ in CO_2 is changed in comparison with that in air. The influence of monochromatic radiation on $\sqrt{\langle T'^2 \rangle}$ was investigated theoretically in [35].

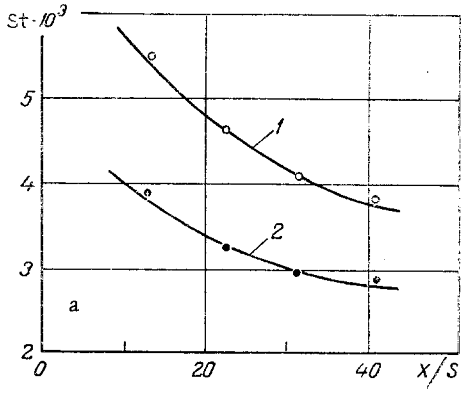
In Fig. 4a we present the results of measurement of the average temperature in the zone of the turbulent core and the overlayer of the boundary layer using the resistance microthermometer and the shielded thermocouple of the combined sensor, in the radiation field and in its absence, in CO_2 and in air, while in Fig. 4b we present the velocity profiles measured with the combined sensor. The experimental values of the temperature were used to calculate the gas density. It is seen that the maximum difference in the temperature profiles in CO_2 and in air in the radiation field does not exceed 15%, while the velocity profiles differ by no more than 3% under identical flow conditions. The temperature is lower in CO_2 than in air, which agrees with the data of Fig. 2 for $y > 55$ μm. The influence of radiation on the temperature profile in a layer of H_2O did not exceed 7% in [17], while the temperature profiles measured with a thermocouple in a turbulent boundary layer of CO_2 in [19] also changed by no more than 14% in comparison with those in air. The velocity and temperature profiles (Fig. 4) in the radiation field and in its absence, in CO_2 and in air, were described by a power-law function [36]. The first velocity measurement corresponded to a minimum distance $y \approx 225$ μm from the wall. One can note that there is a similarity in the velocity and temperature distributions (Fig. 4) with an error not exceeding 10%. The results presented in Fig. 4 and the data of [17, 19] allow us to conclude that the turbulent mechanism of transfer of heat and momentum in an IR radiation field in CO_2 has the dominant influence on the formation of the temperature and velocity profiles in the investigated range of the parameters, and that IR radiation has a rather small influence on the temperature and velocity pulsations in the zone of the turbulent core of an optically thin boundary layer.

In the tests (Figs. 2-4), the CO_2 layers had the following optical depths $\tau = \varkappa\bar{\delta}$: for the sublayer $\tau_S = 1.3 \cdot 10^{-4}$, for the turbulent core $\tau_T = 0.6 \cdot 10^{-3}$, and for the CO_2 layer between the source of IR radiation and the boundary layer $\tau_{la} = 0.18$; here $\varkappa$ is the absorption coefficient, calculated in accordance with [37]; $\bar{\delta}$ are the thicknesses of the layers. The parameter of radiative-convective heat exchange is $N \approx 0.1$.

IV. Heat and Mass Exchange in an IR Radiation Field in the Presence of Tangential and Porous Injection of CO_2 into the Turbulent Boundary Layer

Heat exchange under the conditions of tangential and porous injection at the surface in the absence of radiation has been considered, e.g., in [31, 38, 39]. The action of a radiation field on energy transfer in the presence of the two types of injection can be displayed both using the volumetric absorption of radiation by the medium and through the radiative boundary conditions. The influence of porous injection on heat exchange in a radiation field was studied theoretically in [4, 15] and experimentally in [40]. Curtain cooling by tangential injection in an IR radiation field has hardly been investigated. Porous injection is of interest not only as an effective means of reducing heat fluxes but also as a method of simulating the influence of the injection of products of vaporization of melting surfaces in an IR radiation field [16, 41]. The test bed created [18] and the measurement procedure described above enabled us to obtain experimental data on the combined influence of an IR radiation field and two types of CO_2 injection on the heat exchange for different radiative boundary conditions (Fig. 5) under the conditions $T_w > T_e$.

In Fig. 5a we present experimental data on the influence of tangential injection of air into air and of CO_2 into CO_2 for a turbulent boundary layer at an impermeable, practically mirror plate ($r_w \approx 0.95$) in a radiation field with the discharge of two jets from a combined nozzle for which the height of the lower cut was 10.0 mm while the upper nozzle cut of the main stream was 20 mm. The Stanton numbers St(X) were calculated from the function $St(X) = (q_w(X))/(\rho_e U_e C_{P_e}(T_w - T^*_w))$ of [39], where T_w is the measured temperature of the plates in the



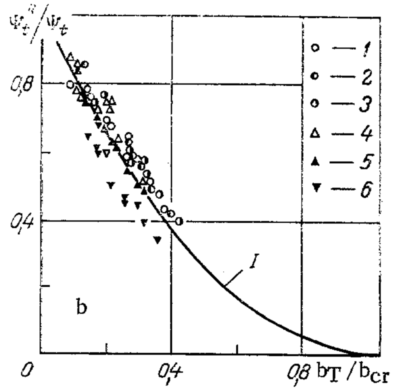


Fig. 5. Heat exchange in the presence of tangential and porous injection of air and CO_2 on the surface over which flow occurs in an IR radiation field: a) injection through a slot: $q_{rad} \neq 0$, $Re_{S_1} \approx$ idem, $Re_{S_2} \approx$ idem, $r_w \approx 0.95$, $S_1 = 10$ mm, $S_2 = 20$ mm; 1) air; 2) CO_2; b) porous injection: $q_{rad} \neq 0$, $\varepsilon = 0.5$; 1) calculation of [31]; air: 1) $N_{k,R} = 0$; 2) 250; 3) 490; CO_2: 4) $N_{k,R} = 0$; 5) 250; 6) 490.

presence of injection and of radiation partially absorbed by the plates; T^*_w is the temperature of the thermally insulated, practically mirror plate under the conditions of injection but in the absence of radiation; $q_w(X)$ is calculated from the known absorptivity of the plates ($r_w \approx 0.95$) and the emissivity and temperature of the source of IR radiation. In the experiments we monitored the temperatures and velocities at the exits from the nozzles, the CO_2 concentration with a VTI-2 instrument, and the consumption of gas in injection with an RS-7 rotameter. Figure 5a shows that in the injection of CO_2 into CO_2 the efficiency of curtain cooling is 30% lower than in the injection of air into air for $Re_{S_1} \approx$ idem, $Re_{S_2} \approx$ idem, $Re_X \approx$ idem, $q_w \approx$ idem, and $T_w > T_e > T_{S_1}$, where T_{S_1} is the temperature at the cut of the lower nozzle. This is due to complicated processes of interaction of the radiation and temperature fields (Fig. 2). The error in determining the Stanton numbers did not exceed 5%.

Figure 5b provides quantitative information about the influence on the dimensionless coefficient of heat transfer of porous injection of air and CO_2 into a turbulent boundary layer of air in an IR radiation field. The emissivity of the porous steel plate was $\varepsilon_w = 0.5$. The coefficient of heat transfer is up to 40% lower in the porous injection of CO_2 into air than in the injection of air into air. The accuracy of the determination of the coefficient of heat transfer $\bar{\Psi} = \Psi R_t/\Psi_t$ in this case was 12%. The combined influence of porous injection and IR radiation is described in more detail in [40].

Thus, the quantitative data obtained (Figs. 2-5) showed the special role of the sublayer of molecular heat conduction (the laminar sublayer) in the reorganization of the temperature field in an optically thin, turbulent boundary layer of CO_2 on a practically mirror plate in an IR radiation field, the considerable deformation of the temperature profile in the vicinity of the wall and the presence of a source of heat release in the laminar sublayer in CO_2 under the action of a radiation field, the weak influence of IR radiation on the temperature and velocity fields in CO_2 in the zone of the turbulent core of the boundary layer, the considerable influence of porous and tangential injection of CO_2 on convective heat exchange in a radiation field, and the necessity of allowing for radiative effects of thermal interaction in an optically thin, turbulent boundary layer for different radiative boundary conditions when calculating radiative–convective heat exchange.

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