Journal of Applied Mechanics and Technical Physics, Vol. 47, No. 5, pp. 637–642, 2006

EFFECT OF ACOUSTIC DISTURBANCES ON A FREE CONVECTIVE FLOW

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UDC 536.24

A gas-dynamic flow in an axisymmetric convective jet is studied experimentally. It is demonstrated that the jet flow with Grashof numbers $\mathrm{Gr} = (0.4\text{–}2.0) \cdot 10^6$ *is self-similar. Acoustic oscillations directed perpendicular to the axis of symmetry transform the profiles of the gas-flow parameters; two temperature maximums located outside the axis can appear. The results obtained indicate that flow instability is generated in high-gradient regions.*

Key words: *jet, free convective flow, acoustic disturbances.*

Introduction. Free (natural) convection arises if the heated object is located into a liquid or a gas whose density is a function of temperature [1]. Free convective flows are studied in problems of heat power engineering, chemical technology, climatology, ecology, and other fields of science and engineering [2–4].

For most flows, the difference in intensity of laminar and turbulent transfer is fairly large. The origin of turbulence is often caused by receptivity and susceptibility of the laminar flow to small perturbations generated by vibrations, acoustic oscillations, pulsations of external flows, or fluctuations of heat release of the heated surface [2]. Disturbances can be inserted into the flow at an arbitrary place and at different times, they can increase or decrease in amplitude under the action of the buoyancy, pressure, and friction forces, or decay.

Experimental and theoretical studies show that free convective flows are sensitive to small perturbations. Typical features of such processes are distortions of thermo-gas-dynamic profiles, formation of waves of the Tollmien–Schlichting wave type, origination of instability, transition, and flow turbulization [2]. These processes have been studied in more detail for gas flows in boundary layers on flat plates and in the case of flow separation [5–9].

The objective of the present work was to study the profiles of gas parameters in an axisymmetric jet from a steady source of heat with a flat surface in the presence of acoustic oscillations.

The acoustic waves were generated in the direction perpendicular to the axis of symmetry of the jet.

1. Subject of the Study and Experimental Technique. A free convective jet in an open space without side walls was formed by a steady heat source (electric oven) shaped as a cylindrical disk (Fig. 1). Electric heating elements were located inside the disk. A copper plate 0.19 m in diameter was placed on the disk surface to make the profiles of temperature T_w and heat-flux density q_w more uniform and to ensure uniform heating. The plate thickness (1 cm) was chosen from the conditions $(T_w - T_{w0})/T_{w0} < 0.01$ and $(q_w - q_{w0})/q_{w0} < 0.01$, where T_{w0} and q_{w0} are the temperature and heat-flux density in the center of the plate.

The temperature T and the velocities u and v in the x and y directions, as well as the heat-flux density q_w along the y axis were measured in the experiments by a Chromel–Alumel thermocouple with a 0.2-mm junction diameter, a hot-wire anemometer, and a heat-flux probe by the method described in [11]. Fluctuations of the gas temperature T' were measured by a hot-wire anemometer with a platinum wire 20 μm in diameter. The high-frequency component of the flow velocity was measured by a balance transducer in the return circuit of the hot-wire anemometer [12, 13]. In addition, the temperature and gas-velocity fluctuations were determined by calibrating the hot-wire anemometer and a microthermocouple connected to it. The probe was placed into a laminar air flow

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Tomsk State University, Tomsk 634050; fire@fire.tsu.tomsk.su. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 47, No. 5, pp. 27–33, September–October, 2006. Original article submitted August 5, 2002; revision submitted October 19, 2005.

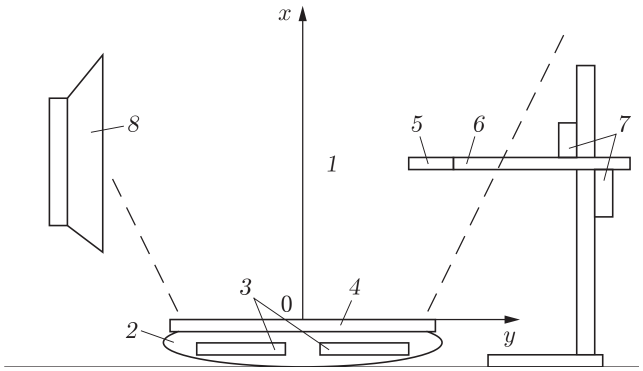

Fig. 1. Layout of the experiment: 1) jet; 2) electric oven; 3) heating elements; 4) copper plate; 5) probe; 6) rod; 7) traversing gear; 8) loudspeaker.

generated by an MT-324 low-turbulence wind tunnel. The laminar air flow was heated to a fixed temperature, and the probe was calibrated in terms of velocity. After that another temperature of the flow was fixed, and the calibration was performed again, etc. Such a technique is similar to the method of correction used to reduce the temperature error of the hot-wire anemometer, in which an identical thermistor not exposed to the flow is located in the vicinity of the main thermal transducer [12].

The probes for measuring T, q, u, and v (see Fig. 1) were rigidly attached to a rod connected to a traversing gear (the $0x$ and $0y$ scales were graduated by 1 mm) and were placed into the working section of the convective jet.

The structure of the probes was chosen to ensure the minimum action on the convective-jet parameters. The diameter of the ceramic rod (see Fig. 1), which was a thermally insulated element, was varied from 2 to 8 mm, which induced no differences in probe readings. The probe was inserted into the jet from the side of the undisturbed ambient medium by rotating the drums of the traversing gear. The time of recording the jet parameters at the control point was 10–15 sec. The results obtained were compared with other available data for validation.

Acoustic oscillations perpendicular to the convective flow were excited by a loudspeaker and were defined by a GZ-type generator. The total errors in determining the parameters were $\delta T \leqslant 4.5\%$, $\delta u = \delta v \leqslant 9\%$, and $\delta q \leqslant 10\%$. The confidence intervals were calculated on the basis of results of 3–5 tests with a confidence probability of 0.95.

2. Results of Measuring the Temperature and Velocity Profiles. Figure 2 shows the temperature profiles; the gas velocities in the absence of acoustic oscillations are listed in Table 1. The solid curves in Figs. 2–4 are approximations by a fourth-power polynomial. The approximation error was within 4.2%. The gas temperature reaches the maximum values near the heat source, decreases further downstream, and acquires value close to constant beginning from the cross section $x = 0.05$ m (curve 4 in Fig. 2), which is caused by the input of the cold gas from the ambient medium through the side surface of the convective jet and by formation of a common flow. Beginning from the coordinate $x = 0.08$ m, the temperature along the axis of symmetry decreases by the power law $T_0 - T_\infty = Nx^n$ [2], where $N = 1.51$ and $n = -1$, which means the transition to the self-similar flow region.

Data processing was performed in self-similar variables [2] $\eta = (y/x)\sqrt[4]{\mathrm{Gr}(x)}$, $\mathrm{Gr}(x) = g\beta x^3(T_0 - T_\infty)/\nu$, $\Phi(\eta) = (T - T_\infty)/(T_0 - T_\infty)$, and $f'/\eta = ux/\sqrt[\nu]{\mathrm{Gr}(x)}$, where $f' = \partial f/\partial n$; f is the stream function. The results of this processing are plotted in Fig. 3 (different points correspond to data obtained in different test series under identical conditions). The computed results and experimental data are seen to be in reasonable agreement in the self-similar region of the gas flow.

Figure 4 shows some results of gas-temperature measurements for the convective jet affected by acoustic oscillations. It is seen that acoustic oscillations transform the gas flow in the convective jet. In addition, two temperature maximums appear in the boundary region, the magnitude of the farther maximum (with respect to the source of sound) being greater. This difference is most clearly visible for $\nu = 15$–300 Hz at moderate distances from the heat source $x = 0.01$–0.03 m (see Figs. 2 and 4).

3. Mechanism of Interaction of Acoustic Oscillations with the Gas-Flow Field in the Convective Jet. Galliulin et al. [14] considered a fluid flow in a cylindrical channel under the action of high-frequency oscillations $H \gg 1$ [H^2 is the ratio of the unsteady (oscillatory) force to viscous forces]. The depth where the action of viscous

TABLE 1

y, m	u, m/sec	
	$T = 344$ K; $x = 0.03$ m	$T = 320$ K; $x = 0.08$ m
0	3.72	2.96
0.03	4.61	4.77
0.06	5.07	4.55

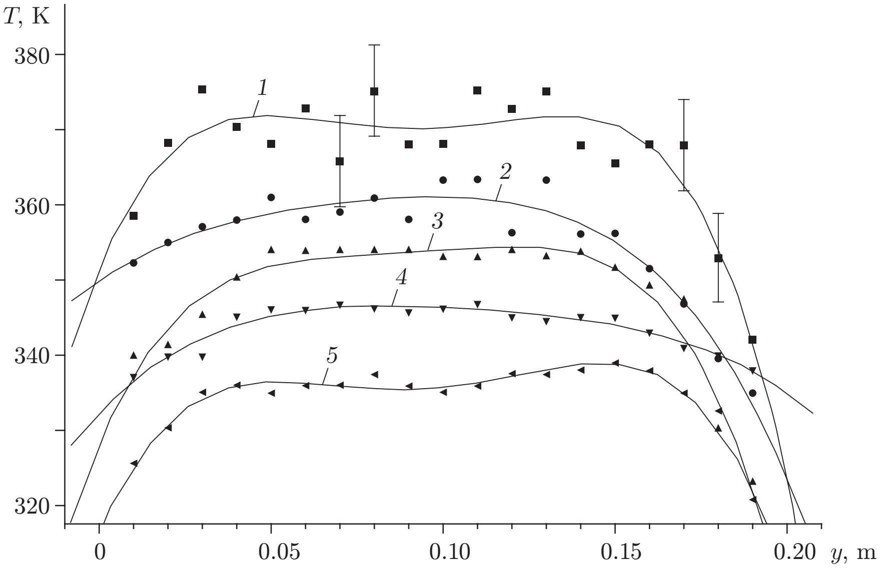

Fig. 2. Gas temperature in different cross sections of the jet: $x = 0.01$ (1), 0.03 (2), 0.04 (3), 0.08 (4), and 0.12 m (5).

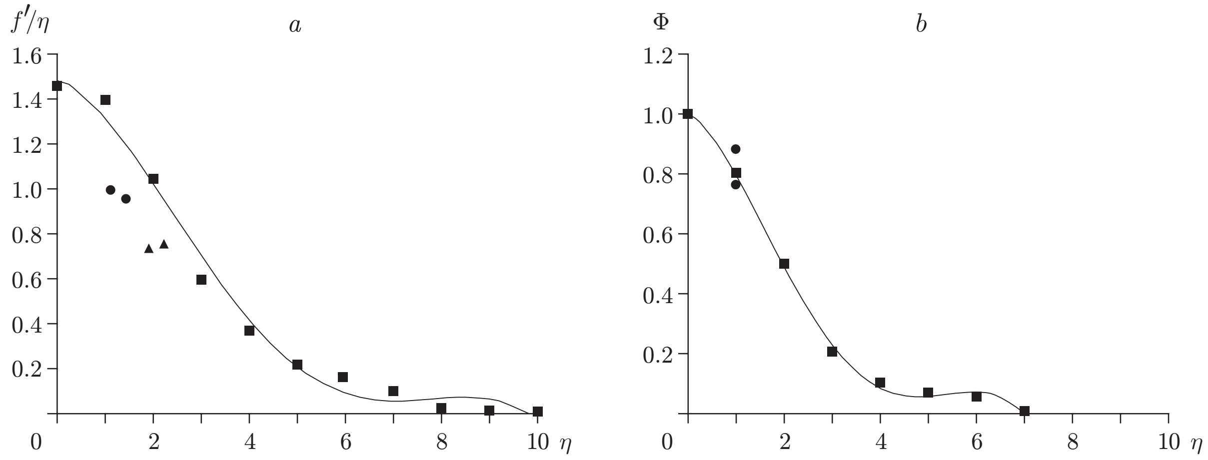

Fig. 3. Velocity (a) and temperature (b) of the gas in self-similar variables: the solid curves show the results computed by the theory [2] for an axisymmetric vertical flow with a point heat source; the points refer to the experimental results.

forces is manifested is much smaller than the body size, vorticity is concentrated in a thin layer near the walls (which reduces the forces of inertia in the vicinity of the channel walls), and the pressure gradient $\partial p/\partial x$ is identical for all points of the channel cross section. Therefore, the near-wall flow responses to a change in pressure faster than the axial flow. It was shown [14] that the maximums of velocity and temperature of the fluid are shifted from the axis of symmetry toward the wall. Such a displacement of the maximums of flow parameters is called Richardson's annular effect [14].

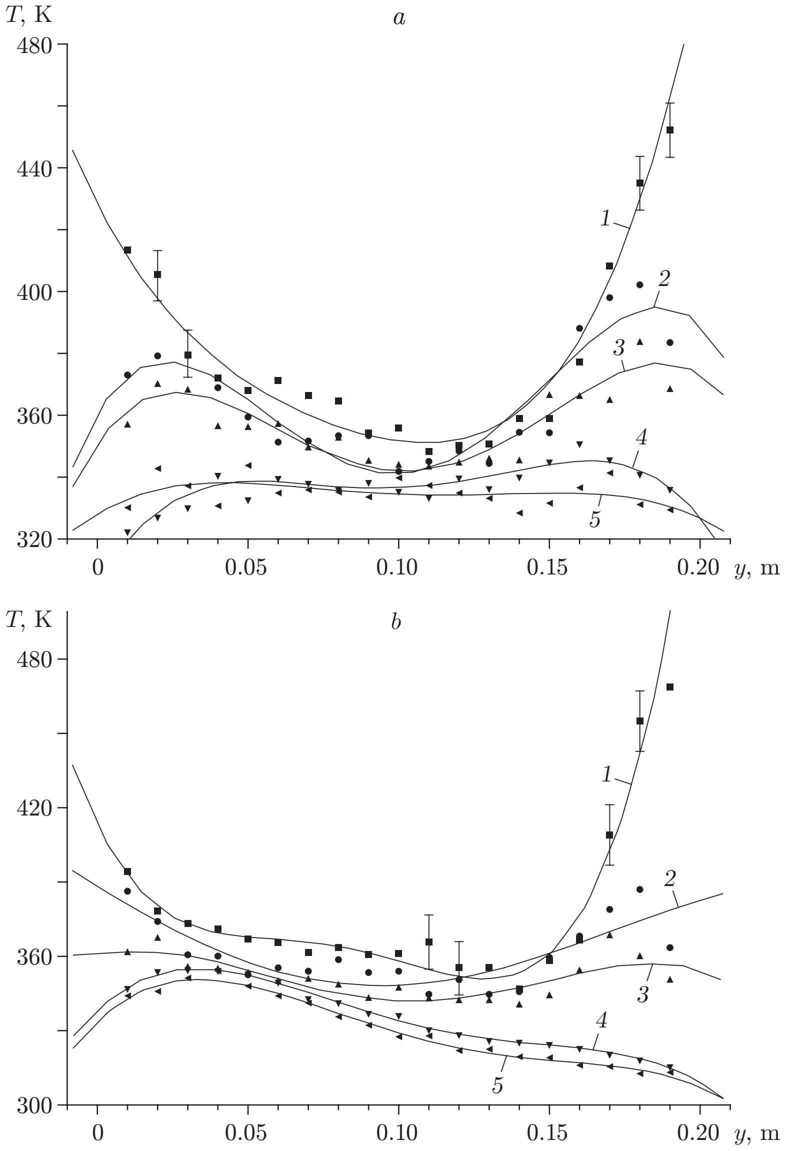

Fig. 4. Gas temperature in the jet under the action of acoustic oscillations with frequencies $\nu = 15$ (a) and 100 Hz (b); notation the same as in Fig. 2.

The displacement of the maximums of flow parameters in a convective jet under the action of acoustic oscillations perpendicular to the jet, which was obtained in the present experiments, is similar to Richardson's annular effect. According to the Rayleigh–Tollmien theory, hydrodynamic instability arises and increases at points of infection of velocity profiles [15], i.e., at points with the maximum gradient of velocity. In a convective jet, the points of inflection of velocity profiles are located at the points of the maximums. We computed the spectral densities C_{kT} of fluctuations of the temperature T' in the near and far points of inflection of temperature profiles corresponding to frequencies $\nu = 15$ and 100 Hz by the formula

$$C_{kT} = \sqrt{\Big(\Delta t \sum_{i=1}^{k} \frac{T'}{T}\,\cos\left(2\pi\nu\Delta t i\right)\Big)^2 + \Big(\Delta t \sum_{i=1}^{k} \frac{T'}{T}\,\sin\left(2\pi\nu\Delta t i\right)\Big)^2}$$

with $\Delta t = 0.005$ sec and $k = 100$. The computation results were $C_{kT} = 0.41$ and 0.39 for $\nu = 15$ Hz and $C_{kT} = 0.33$ and 0.37 for $\nu = 100$ Hz.

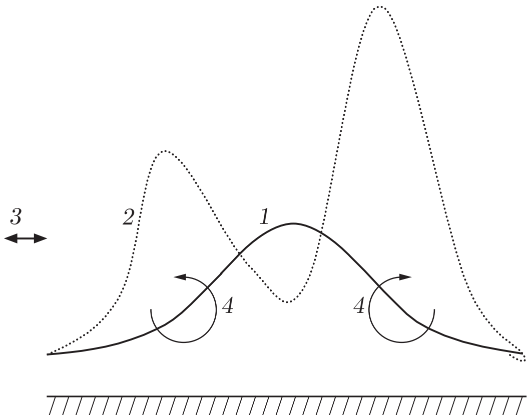

Fig. 5

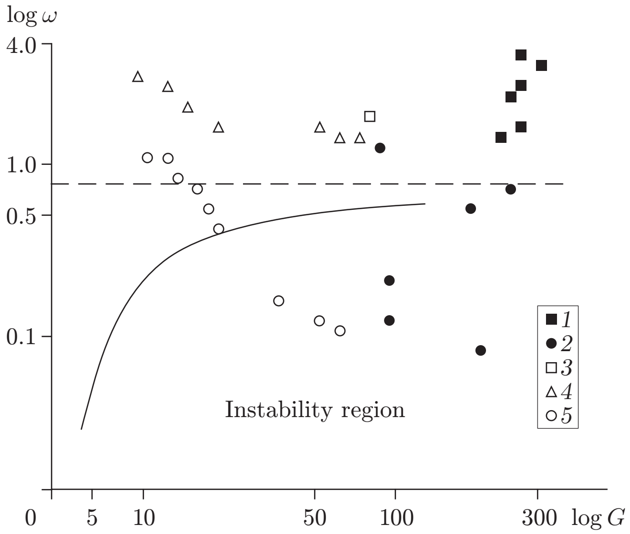

Fig. 6

Fig. 5. Mechanism of origination of gas-flow instability: 1) schematic image of the temperature profile in the absence of acoustic oscillations; 2) the same image under the action of acoustic oscillations; 3) direction of gas oscillations; 4) vortices.

Fig. 6. Flow stability diagram: the solid curve shows the calculated results [2]; the points are the experimental data (points 1 and 2 are the data of [2] for a convective jet with vibrations of the heat source; points 3–5 are the results of the present work); the dashed line shows the limit of inviscid instability.

The spectral analysis shows that oscillations with frequencies $\nu = 15$ and 100 Hz contribute significantly to the energy of turbulent fluctuations at the points of inflection of flow parameters. Acoustic oscillations with frequencies $\nu = 15$ and 100 Hz intensify oscillations of particles, i.e., resonant addition of the amplitudes of gas oscillations occurs. Crossflow oscillations of the gas in the acoustic wave correlate with gas oscillations at the points of inflection of the profiles of flow parameters. Based on the temperature fluctuations measured at these points, we found the correlation function

$$R_{T,\nu} = \sum_{i=1}^{k} T_i^1 \cos(2\pi\nu\Delta t i) \Bigg/ \left(\sqrt{\sum_{i=1}^{k} T_i'^2} \sqrt{\sum_{i=1}^{k} \cos^2(2\pi\nu\Delta t i)} \right).$$

In the near and far maximum points (Fig. 5), $R_{T,\nu} = 0.31$ and 0.29 for $\nu = 15$ Hz and $R_{T,\nu} = 0.34$ and 0.22 for $\nu = 100$ Hz. Hence, the interaction of acoustic disturbances with gas oscillations has a resonance character. Instability originates in high-gradient zones, the vortices formed (see Fig. 5) entrain the gas from more heated central regions toward the periphery, and the temperature in these zones increases. The far maximum of temperature is expected to be higher than the near maximum, because the far maximum results from addition of the amplitudes of acoustic oscillations with respect to the cold gas in the acoustic wave with gas oscillations, whereas the near maximum results from addition of the amplitudes of acoustic oscillations of the gas heated in the jet portion close to the axis. The proposed mechanism of interaction of acoustic oscillations with nucleating vortices at the points of inflection of gas-flow profiles in a convective jet offers an explanation for the appearance of two temperature maximums.

Figure 6 shows the results of experiments plotted against the stability diagram obtained in [2] by solving the Orr–Sommerfeld equations for the amplitude functions of disturbances [16] of a planar plume in the variables $G = 4(\mathrm{Gr}/4)^{1/4}$ and $\omega = 32\pi\nu\rho x^3/(G^3\mu)$, where ρ and μ are the density and dynamic viscosity of the gas. The stability diagram describes the trajectory of a disturbance with a constant frequency ν and allows one to determine the change in disturbance amplitude in the downstream direction, i.e., with increasing x (or G). The neutral curve divides the regions of damping and amplification of disturbances in the flow. If the values of G are low, the disturbances decay. The damping region is separated from the region of amplifying disturbances by the neutral curve. It is seen that the main flow in the convective jet amplifies acoustic oscillations whose frequency does not exceed some critical value, but all these disturbances decay when moving downstream, which is confirmed by direct measurements and does not contradict the proposed mechanism of interaction of acoustic disturbances with the gas flow.

Conclusions. Receptivity of a convective flow from a steady axisymmetric heat source to acoustic oscillations directed perpendicular to the uprising flow in the range of frequencies $\nu = 15$–1500 Hz has been experimentally examined for the first time.

It is shown that acoustic oscillations transform the profiles of gas parameters in the boundary layer of a convective jet, where two temperature maximums appear.

A mechanism of interaction of acoustic oscillations with vortices emerging at the points of inflection of gas parameters in the convective jet is proposed.

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