Observation of structural levels of turbulent heat transfer

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A stratification of heat transfer into discrete levels has been observed experimentally in an interaction of an acoustic field with a turbulent boundary layer in a supersonic channel. The squares of the heat-transfer rate coefficients corresponding to different levels are multiples of each other. © *1995 American Institute of Physics.*

The properties of internal turbulence structures in hydrodynamic turbulence[1–4] and their relationship with corresponding entities in nonlinear optics, acoustics, and radiophysics[5] are attracting particular interest in research on the nature of the interaction of external fields with a turbulent medium. The susceptibility of a turbulent shear layer is manifested in a selective transformation of acoustic perturbations into vortex perturbations in narrow frequency intervals.[6] Although a generation of intrinsic oscillations is observed in a laminar layer,[7] the nature of the acoustic interaction with well-developed turbulence and the properties of the internal turbulence structures themselves remain very unclear.

In this letter we are reporting a study of the effect of an acoustic field on heat transfer in a turbulent boundary layer under conditions of an elevated anisotropy of the flow.

The experiments were carried out on the RD large-scale gasdynamic apparatus (Institute of Theoretical and Applied Mechanics, Novosibirsk), which provides high Reynolds numbers, with air flow rates up to 10 kg/s. We measured distributions of the heat-transfer rates, the pressure, and the pressure fluctuations at the walls of a supersonic channel as a function of the position of the channel axis with respect to the incoming subsonic gas flow, in which intense natural acoustic waves were in turn excited.

The gas (air) which passed through the entrance channel 1 (Fig. 1) entered closed cavity 2 and then reached the entrance of a second channel, 3, which had the shape of a conical Laval nozzle. The angle of the generatrix of the subsonic part of the nozzle was 32°, and that of the supersonic part was 8°. The diameter of the critical cross section was 38.4 mm. The position of the nozzle was chosen in such a way that the angle between the axes of channels 1 and 3 took on the values $\beta=0°$, $10°$, and $20°$. The Mach numbers of the gas flowing out of channel 1 were $M_1=0.1$, 0.2, and 0.35. The total pressure at the exit from this channel was $p_0=(19.1-19.5)\times 10^5$ Pa. The Reynolds number calculated from the diameter of channel 1 was $\mathrm{Re}=(3-9)\times 10^6$.

The method for measuring the local heat exchange heat-transfer rates, which includes an original method for calibrating the detectors, is described in Ref. 8. Temperature pickups were placed along the generatrix of the nozzle at points (4 in Fig. 1)

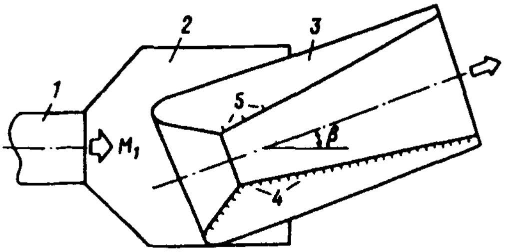

FIG. 1. Experimental layout. 1—Entrance channel; 2—closed cavity; 3—nozzle; 4—surface-temperature pickups; 5—pressure-fluctuation pickups.

separated by distances of 5 mm (there were a total of 40 such points). The relatively fast response time of these detectors made it possible to achieve high values of the heat-transfer rate $\alpha = q/(T_w - T_w^*)$, where q is the heat flux density at the wall, T_w is the temperature of the wall surface, and T_w^* is the restoration temperature at the wall. The random error in the measurements of α for the heat transfer was less than 5%, while the total error ranged up to 10%. In the experiments we used a computer-controlled data acquisition and analysis system which sampled the temperatures of the detectors at 50 Hz. Pressure fluctuations were monitored by strain gauges fabricated at the Institute of Theoretical and Applied Mechanics, with a sensitive element 1.5 mm in diameter. The signals from these detectors were fed to the input of an amplifier, digitized in a SPEKTR-ÉVM MERA-60 system, and stored. The frequency of the discrete sampling was 25 kHz. The error of these measurements was 1.5%. We used three pickups, embedded in the wall of the nozzle at intervals of 10 mm along a generatrix of the nozzle (5 in Fig. 1). By rotating channel 3 around its axis, we changed the position of the generatrix with the measurement points with respect to the heat flux. The measurements were carried along the lower generatrix ($\gamma = 0°$) and along the upper generatrix ($\gamma = 180°$) of the channel.

To determine the qualitative nature of the flow, we used a shadow method for optical visualization on a special apparatus in a planar analog of the experimental model. It was found that a turbulent jet approximately the same as the calculated one issuing from entrance channel 1 interacts with the flow near the wall along subsonic part of channel 3, in which there is a partial rotation of the jet toward the rotated channel 3. In the supersonic part, the main flow is finally rotated to the direction of the axis of channel 3. In the layer of the displacement of the jet issuing from channel 1, large-scale structural formations develop. These formations then dissipate under the influence of acceleration in channel 3.

The pressure fluctuations (at points 5 in Fig. 1) were measured at $M_1 = 0.35$ at the specified values of γ and β. A characteristic feature of the spectra of these fluctuations is the presence of a discrete line near $\nu = 1.75$ kHz and the second harmonic of this frequency. The behavior of this discrete line as the parameters β and γ are varied indicates that the source of this line is a shear layer of gas near the entrance channel and that intense coherent acoustic waves (discrete lines) then interact with the turbulent flow in the boundary layer at the walls of channel 3.

Figure 2a shows the distribution of the heat-transfer rate $\alpha = q/\Delta T$ along a genera-

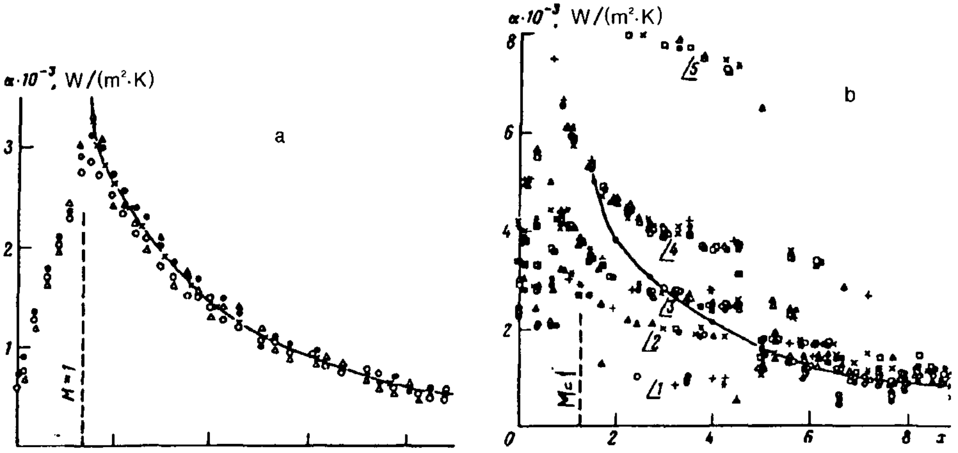

FIG. 2. Distribution of the heat-transfer rates along generatrices of a nozzle. Here $x=X/R^*$. a: $M_1 \leq 0.1$, $\beta=0°$. The curve is a calculation from Ref. 9. b: $M_1=0.35$, $\beta=20°$. 1–5—Structural levels of heat transfer; curve—calculation (Ref. 9, $\beta=0°$).

trix of channel 3 in the case $\beta=0°$, at a small value of the Mach number in the flow issuing from channel 1 ($M_1 \leq 0.1$). These experimental data can be described well by the asymptotic theory of a turbulent boundary layer[9] (the curve).

When we superimpose either the experimental data (with $\beta \neq 0$, $M_1 > 0.1$) from several experiments carried out under identical conditions or data from several samplings found in a single experiment, we observe a clearly detectable, qualitatively new aspect of the behavior of the coefficients α. This new aspect can be summarized as follows. Near the generatrix of the nozzle corresponding to the region of deviations of the pressure at the wall from their unperturbed values, the coefficients α are distributed in a random way among three to five levels, whose number increases with increasing β and M_1 (reaching a maximum of 5). Just beyond this region the experimental points converge on a single level, close to the α distribution for $\beta=0°$ and $M_1 \simeq 0$.

Figure 2b shows data from four experiments with three samples of α (the sample corresponds to a one-time polling of all 40 measurement points) in each, found for $M_1=0.35$, $\beta=20°$, and $\gamma=0$. Note the clearly visible positions of the experimental points along each line of levels and the obvious preference for the intermediate levels.

To analyze the probability that the experimental values of α would fall in the various levels, as a function of the parameters M_1, β, and γ, we plotted diagrams of the distribution of α among levels. As a control we adopted a section of a generatrix of the channel in the region $X/R^* = 1.0$–5.0, where R^* is the radius of the critical cross section of the nozzle (where the Mach number is $M=1$). The original file of experimental points was equal to the sum of the experimental data from 12 samples (194 points). By calculating the number of points at each level, we determined the probability P_n for reaching this level. We then found an average value of α_n in the control region for each level.

On the diagram of the probabilities P_n (Fig. 3), we plotted average values of α_n for

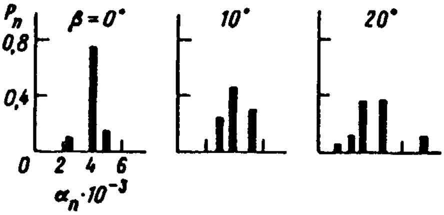

FIG. 3. Effect of the nozzle inclination on the spectra (these are averages along a control region) of levels of the heat-transfer rates for $M_1 = 0.35$.

each level along the control region along the abscissa axes. Here we can use the normalization relation

$$\sum_{n=1}^{N} P_n = 1,$$

where N is the number of levels seen experimentally. With increasing β, at the fixed value $M_1 = 0.35$, the number of levels in the spectrum, α_n, increases. We find a similar result when we hold β constant and vary M_1. We find a similar pattern at the upper generatrix of channel 3 ($\gamma = 180°$). The only difference is that, as β or M_1 increases, the spectrum α_n becomes deformed in a different way. At the upper generatrix of the channel we observe an increase in the populations of the low-lying levels of the heat-transfer coefficients, while at the lower generatrix we find the opposite trend.

Analysis of these results reveals a completely definite relationship among the values of α_n^2 (Fig. 2b, $n = 1-5$) in an arbitrary cross section X/R^* in the control region of the generatrix of channel 3: All of them are multiples of the smallest among them (α_1^2). For five arbitrarily selected cross sections $X/R^* = 1.5$, 1.9, 2.0, 2.5, and 4.0, for example, the standard deviation of the ratios α_n^2/α_1^2 from integers is 13%, and it lies within the error of the calculation of these quantities. In 10% of the total number of points, this deviation was less than 0.5%, so there is no possibility of a random coincidence.

The stratification of the turbulent heat transfer to discrete levels and the circumstance that the ratios α_n^2/α_1^2 are multiples of each other constitute evidence of a special mechanism for the interaction of the coherent acoustic field with the anisotropic turbulence, because of the internal structure of this turbulence.

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