

# Preface

This monograph describes the results of systematic investigations of the authors in the field of stability and initial stages of the laminar-turbulent transition in shear flows of thermally nonequilibrium molecular gases. The dissipative effect arising in such flows due to relaxation of internal degrees of freedom of polyatomic molecules has been recently considered as a tool for increasing stability of these flows and for delaying flow turbulization. Linear stability of plane-parallel shear flows of vibrationally excited gases is studied in the monograph in the general statement. Detailed results on linear and nonlinear stability of a plane Couette flow are presented, including analytical estimates and numerical calculations of the critical Reynolds numbers. Nonlinear evolution of large-scale (coherent) vortex structures and the total cycle of the development of the Kelvin–Helmholtz instability in a thermally excited carrier shear flow are considered.

The mathematical model of flows with relaxation at moderate levels of excitation is based on the full Navier–Stokes equations for a viscous heat-conducting gas with allowance for bulk viscosity. The case of a strongly nonequilibrium vibrationally excited gas is described by the full system of equations of two-temperature aerogasdynamics, where relaxation of vibrational modes is simulated by the Landau–Teller equation for vibrational temperature. The monograph will be useful for aerodynamicists, physicists, mathematicians, and students performing research in the field of hydrodynamic stability theory, turbulence, and flow laminarization.

The book contains an Introduction and seven chapters. The modern status of investigations of the influence of relaxation processes on hydrodynamic stability and turbulence suppression is reviewed in the Introduction. In particular experiments on application of the dissipative effect for control of the laminar-turbulent transition in real hypersonic flows are described.

Chapter 1 has an introductory character and provides some auxiliary material to give an idea of notions and results of physical kinetics, kinetic theory, and acoustics of molecular gases, which are used in the book. The main goal of this chapter is to demonstrate the feasibility and adequacy of mathematical models used in the authors research. In particular the evolution of the concept of bulk viscosity in mechanics and kinetic theory of gases is briefly described, because this

phenomenon is still disputable in aerodynamics. Qualitative properties of the Landau–Teller relaxation equation for the vibrational mode energy, which plays a key role in subsequent considerations, are discussed. The physical mechanism of dissipation of acoustic waves on the background of the relaxation process in a thermally nonequilibrium molecular gas is described.

Chapter 2 is devoted to investigations of linear stability of plane-parallel flows of an inviscid nonheat-conducting vibrationally excited gas. Some classical results of the theory of linear stability of ideal gas flows, in particular the first and second Rayleigh’s theorems and Howard’s theorem, are generalized. An equation of the energy balance of disturbances is derived, which shows that vibrational relaxation generates an additional dissipative factor, which enhances flow stability. Calculations of the most unstable inviscid modes with the maximum growth rates in a free shear layer are described. It is shown that enhancement of excitation of vibrational modes leads to reduction of the growth rates of inviscid disturbances.

Chapter 3 describes the results of numerical and analytical studies of linear stability of a supersonic Couette flow of a vibrationally excited gas. Even and odd inviscid modes of disturbances are analyzed as functions of the Mach number, depth of excitation of vibrational levels, and characteristic relaxation time. The general structure of the spectrum of plane perturbations is studied for finite Reynolds numbers. Two most unstable acoustic viscous modes are identified. Results calculated using the constant viscosity model and Sutherland’s law are compared. Neutral stability curves are calculated, which show that the dissipative effect of vibrational mode excitation is inherent in both models of viscosity. The relative increase in the critical Reynolds number caused by excitation is approximately 12%.

An asymptotic theory of the neutral stability curve for a supersonic plane Couette flow of a vibrationally excited gas is developed in Chap. 4. The initial mathematical model consists of equations of two-temperature viscous gas dynamics, which are used to derive a spectral problem for a linear system of eighth-order ordinary differential equations. Unified transformations of the system for all shear flows are performed in accordance with the classical scheme. The spectral problem with two boundary conditions, which was not considered previously in available publications, is reduced to an algebraic secular equation with separation into the “inviscid” and “viscous” parts. The properties of the generalized Airy functions are used for asymptotic estimates of “viscous” solutions. The neutral stability curves obtained on the basis of the numerical solution of the secular equation agree well with the previously obtained results of the direct numerical solution of the original spectral problem.

The energy stability theory extended by the authors to the case of compressible flows of a vibrationally excited molecular gas is used in Chap. 5 to study stability of a subsonic Couette flow. In particular a universal approach is proposed for derivation of equations of the energy balance of disturbances for energy functionals that adequately reflect the evolution of the total energy of oscillations for an arbitrary level of thermal excitation. Based on these equations variational problems are posed for determining the critical Reynolds number of the possible beginning

of the laminar-turbulent transition. Their asymptotic solutions are obtained in the limit of long-wave disturbances and yield an explicit dependence of  $Re_{cr}$  on the bulk viscosity coefficient, Mach number, and vibrational relaxation time.

Neutral stability curves are calculated for arbitrary wavenumbers on the basis of the numerical solution of eigenvalue problems. It is shown that the minimum critical Reynolds numbers in realistic (for diatomic gases) ranges of flow parameters are reached on modes of streamwise disturbances and increase with increasing bulk viscosity coefficient, Mach number, vibrational relaxation time, and degree of excitation of vibrational modes. The results obtained in the study qualitatively confirm the asymptotic estimates for  $Re_{cr}$ .

Chapter 6 contains the results of the numerical study of a model problem for estimating the influence of thermal relaxation on the turbulized flow outside the limits of the laminar-turbulent transition. Nonlinear evolution of a large-scale vortex structure in a plane shear flow of a molecular gas is considered. Such structures are inevitable attributes of the final stage of the laminar-turbulent transition and turbulence generation in plane wakes, mixing layers, and submerged jets. The results of numerical simulations reported in this chapter lead to a conclusion about a noticeable damping effect of thermal relaxation on nonlinear dynamics of disturbances that can be really reached in nozzle flows, underexpanded jets, or shock waves.

Chapter 7 presents the results of numerical simulations of the full cycle of evolution of the Kelvin–Helmholtz instability, which adequately reproduce the local mechanism of turbulization of the free shear flow. The problem is considered both within the frameworks of the Navier–Stokes equations for a moderate level of thermal nonequilibrium and using the full system of equations of two-temperature aerodynamics for a vibrationally excited gas. Plane waves preliminary calculated by numerical solution of appropriate linearized systems of inviscid gas-dynamic equations are used as initial perturbations. The known pattern of the evolution of the “cat’s-eye” large-scale vortex structure typical for the emergence and development of inertial instability is reproduced in detail. The calculated results show that the relative enhancement of dissipation of the kinetic energy of the structure averaged over its lifetime can reach 12–15% owing to the increase of thermal nonequilibrium in ranges realistic for diatomic gases.

The results presented in the book clearly document the reality of the considered dissipative effect and possibility of its use in control of molecular gas flows.

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Yurii N. Grigoryev  
Igor V. Ershov



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Grigoryev, Y.N.; Ershov, I.V.

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