# Study of Interaction between Swirling Flows and Energy Release

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## 1 Introduction

The swirling flows are ubiquitous in nature and technical applications. Frequently they interact with energy releases of various kinds: chemical energy release in combustion, or energy release from internal degrees of freedom in gas discharge, or Joule heat in electrohydrodynamics, or the heat, associated with a phase transition, or simply energy release from some heating device. Swirl is often used to stabilize combustion in burner devices and inside the combustion chambers of jet engines [1]. Using nonequilibrium state of the medium created with the discharge is often proposed as a flow control tool in aviation. As vortices near the wings or the helicopter rotor blades and the vortex wake behind the aircraft represent the essential features of the flow, it is desirable to control them, using non-mechanical techniques, first of all, thermal and electrical ones. An example of vortex—energy release interaction in nature is tropical storm formation, which is presumably driven by the influence of the heat from condensation upon the structure of a cyclone. In this paper, we extend our previous studies [2, 3], concerning the interaction of a columnar vortex with energy release in nonequilibrium medium with one internal degree of freedom and consider the influence of energy release upon the structure of swirling flow inside a pipe. The results appear to be quite different for these two problems: a free columnar vortex is robust against thermal or nonequilibrium perturbations and only moderate changes can be obtained like moderate increase of azimuthal velocity or transformation into elliptical shape in the case of vortical Rayleigh-Taylor instability, whereas for the swirling flow in a pipe the structure of the flow and the position of recirculation region is remarkably changed even for low energy release values. The reason of this difference is that in the first case an existing vortex is affected and in the second one — the conditions for vortex formation are affected. As in our previous study of von Karman vortex street in nonequilibrium gas [4], it appears much easier to control new vortex formation with energy release than to influence upon an existing vortex.

## 2 Influence of initial nonequilibrium state upon a columnar vortex: the case of a finite energy release region

In our previous studies [2, 3] we considered the evolution of a columnar vortex with initial excitation of the internal degree of freedom in some spot. It appeared that the vortex is transformed into a new

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stationary state with density decrease near the centre of the vortex and little change of azimuthal velocity. The process of the vortex transformation consists of relaxation of the excitation, propagation of the wave, taking away some mass, and — if the centre of excitation spot does not coincide with the centre of the vortex — of complex dynamics, involving the falling of hot gas towards the centre of the vortex, mixing and axisymmetrization of the final state. In [2] the vortex evolution was studied under assumption of infinite length of excitation region along the vortex axis, so that all the parameters depend only on radial coordinate and time. In this paper, we extend our results to the case of localized with respect to axial coordinate excitation of temperature of internal degree of freedom $T_i = T_\infty + \Delta T_i \cdot \exp(-r^2 / D^2)\exp(-z^2 / D_z^2)$. Navier-Stokes equations for compressible fluid with one equation of relaxation of the energy of internal degree of freedom were solved numerically using second-order Godunov method with van Leer TVD-limiter. Only axisymmetrical case is considered because the fully 3D problem requires much more powerful computational resources. It appears that the beginning of the process is similar to 1D case, but after the wave leaves the region, a secondary flow arises due to the pressure difference along the vortex axis. The results of numerical simulations are presented in Fig.1. It is clearly seen that the pressure of hot light gas at the place of initial excitation exceeds that of almost undisturbed gas located above and below. This pressure difference leads to a secondary flow of the gas along the vortex axis upwards for z>0 and downwards for z<0. The resulting loss of the mass near the axis in z=0 section leads to the radial movement of gas towards the axis. Hence, the shape of low-density region is changed and the profile of azimuthal velocity is modified according to conservation of angular momentum. It can be shown that the result of the interaction with initial excitation is amplification of vortex in terms of azimuthal velocity, not weakening as in 1D case. Two azimuthal velocity change profiles are compared in Fig.2: intermediate one, corresponding to t=0.0045 s, which is close to 1D solution, and the final one.

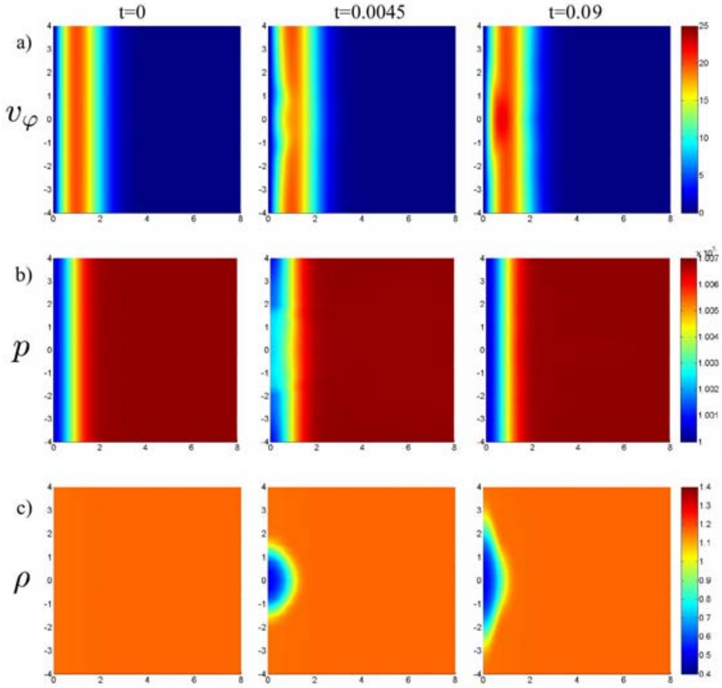

Figure 1. Distributions of a) azimuthal velocity (m/s), b) pressure (Pa), c) density (kg/m$^3$) in meridional plane (r, z). t=0.0045 s corresponds to the moment when the wave leaves the observed region and t=0.09 s corresponds to the final state of the vortex.

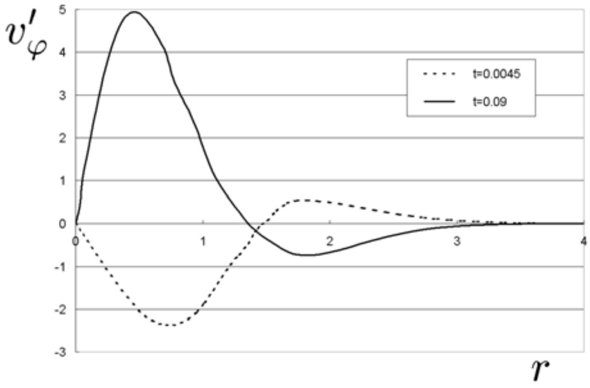

Figure 2. Profiles of azimuthal velocity change (m/s) with respect to initial distribution. Intermediate state for t=0.0045 s is shown with dotted line, the final state — with solid one. The initial vortex has max. velocity 20m/s.

## 3 Development of Rayleigh-Taylor instability

Another way by which the vortex can be modified using the energy release is development of vortical Rayleigh-Taylor instability in the case of internal degree of freedom excitation in an annular region. The idea is to heat the gas in an annulus so that the waves take away some mass and we obtain a vortex with the core, heavy with respect to the surrounding gas. The vortices with heavy core are unstable: the instability is analogous to classical Rayleigh-Taylor one, centrifugal force playing the role of gravity. Numerical simulation was performed using second-order Godunov method. In order to maintain the negative radial density gradient, necessary for the instability development, periodic energy pumping into internal degrees of freedom was used. Its power was moderate, the maximal temperature during the calculation was about 620 K, which is much lower than typical temperatures in the discharge region. Nevertheless, it is enough for development of Rayleigh-Taylor instability. The evolution of density field in Fig.3 shows that the vortex becomes elliptical with two spiral arms. The development of instability is limited by the mass flow along the spiral arms, which eliminates the negative density gradient. The vortex still persists, but with elliptical shape and with vorticity increase in the centre.

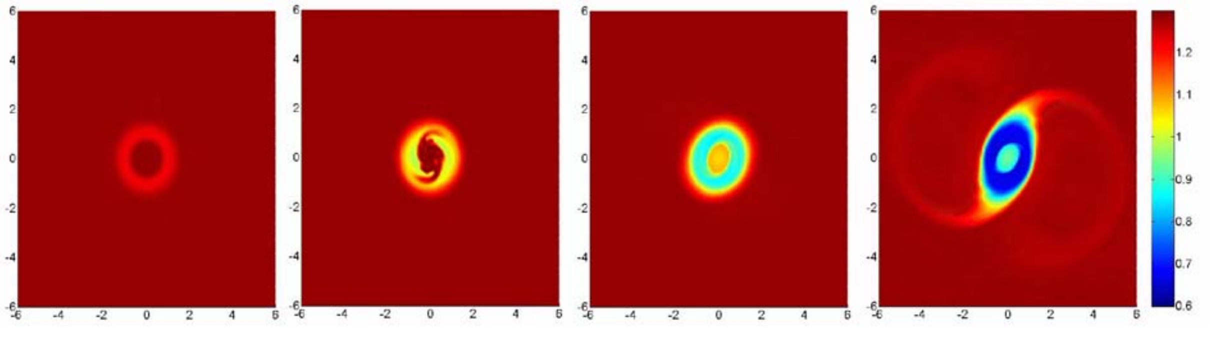

Figure 3. Evolution of density field (kg/m$^3$) during the development of Rayleigh-Taylor instability.

# 4 The influence of energy release upon the structure of swirling flow in a pipe

The swirling flow in a pipe is important not only because of its numerous technical applications, but also because, unlike the free columnar vortex, it can be easily realized in the experiment, and the results of numerical simulation can be compared with experimental data. Numerical simulations of the influence of localized energy release upon the swirling flow with medium swirl parameter $v_{\varphi\max}/v_{z\max}\approx 1$ were performed using second-order Godunov method in cylindrical coordinates. The flow without energy release contains a recirculation region, which moves upstream after activation of energy release. Since the gas moves very slowly near the recirculation bubble, it is strongly affected even by weak energy release. Slowly moving gas receives more heat from the heater or from internal degrees of freedom, and the position of recirculation region is remerkably changed even for heating the gas up to 370 K only. For large values of energy release recirculation region becomes a hot spot in the flow, and affects the whole structure of temperature field downstream. Comparison with experimental data on interaction of the swirling flow with discharge is to be made.

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