Buenos Aires – 5 to 9 September, 2016
Acoustics for the 21st Century…

PROCEEDINGS of the 22nd International Congress on Acoustics

Ultrasound: Paper ICA2016-175

Acoustically induced transitions of CHFD discharge in swirl flow

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Abstract

A mechanism providing acoustically induced generation of helical disturbances on a plasma filament in swirling flows is presented. The numerical simulation shows a formation of a helical structure of the gas flow in the presence of an acoustic standing wave. The flow structure determines the heat flux. In the heated zones, the ionization rate increases and the channel resistance drops that leads to the formation of a new discharge channel, which takes the helical shape of the flow structure. The shape of the simulated helical structure can be matched with the experimentally observed large-amplitude disturbances of the plasma filament in the swirling flow with an excited standing acoustic wave.

Keywords: sound, transitions, swirl flow, discharge

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1 Introduction

The structure formation and dynamics of the electric discharges in swirling flows represents one of the main applied problems in plasma aerodynamics, hydrogen production technology, etc. [1,2]. A discharge structure in the swirling flows can be controlled by the electromagnetic field as well as by gas-dynamic fields [3-5]. Zavershinskii et al. have shown [3] that the transitions between the various forms of CHFD discharge could be initiated by the swirl ratio changing. Zavershinskii et al. [4] and Galechyan et al. [5] have shown that the glow discharge structure could qualitatively change under the influence of the external acoustic field.

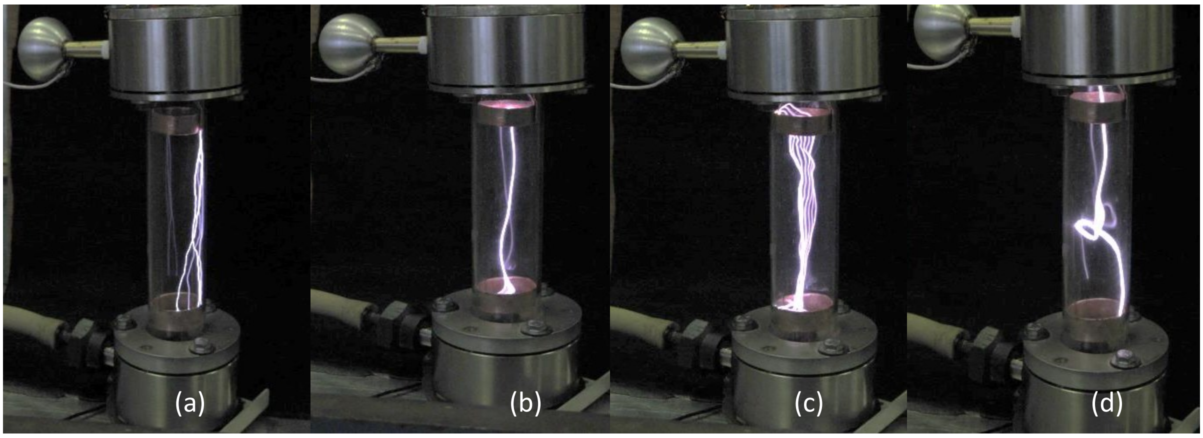
Experimental study of a longitudinal plasmoid was conducted in [6]. The longitudinal plasmoid was created by a pulse repetitive capacity coupled HF discharge (CHFD) in the swirl argon stream at atmospheric pressure in a closed quartz tube. The average electromagnetic power was 200 W at electromagnetic field frequency 0.5 MHz. The pulse duration τ varied between 200 and 500 microseconds. The duct radius was R = 1.8 cm, the length L = 20 cm. The swirl airflow was generated by a simple tangential swirler, Figure 1. The total mass flow rate took values in the range 1–2 g/s.

Source: (Klimov et al, 2010)

Figure 1: The duct scheme from the experimental studies of a longitudinal plasmoid created by the continuous CHFD in swirling flow

There was a single stable longitudinal CHFD plasmoid near the vortex axis at a high pulse frequency f_M = 300÷2000 Hz and low inlet tangential flow velocity v_{in} < 10 m/s, Figure 2a. A surface filamentary HF discharge was observed on a duct wall at a low pulse frequency $f_M \leq 300$ Hz of CHFD and inlet tangential flow velocity v_{in} > 10 m/s, Figure 2b. There was a multi-filament CHFD plasma formation near the vortex axis at a high pulse frequency f_M = 300-2000 Hz and high inlet tangential flow velocity v_{in} >10 m/s, Figure 2c. Analysis of high-speed frames showed that there was a single rotated HF filament in swirling flow in this mode only.

It was revealed that there was a strong plasma-vortex interaction in resonant mode, Figure 2d. Large loop disturbances of HF filament were recorded. The generation and evolution of these disturbances were determined by the acoustic standing wave excited by the electromagnetic pulses in the quartz tube resonator. Indeed, in this mode the pulse modulation frequency f_M range is about of f_M ~ 850 - 875 Hz. This range is closed to the resonant frequency f_S of acoustic standing waves in tube duct $f_S = c_S/2L$ ~ 870Hz (where L is the duct length, c_S is the sound speed in the argon flow heated by CHFD). Therefore, the experimental study of capacitive high-frequency discharge in a quartz duct with swirling flow at various discharge pulse frequencies showed that when the pulse frequency approached the resonant acoustic frequency of the duct, the plasma discharge structure was transformed from a multifilament form to a single filament with a large loop traveling along the tube axis and rotating at the same time.



Source: (Klimov et al, 2010)

Figure 2: A longitudinal plasmoid created by the pulse repetitive capacity HF discharge in the swirling flow (τ = 500 μs). (a) v_{in} ~ 10 m/c, f_M = 100 Hz; (b) v_{in} ~ 10 m/c, f_M = 300 Hz; (c) v_{in} ~ 30 m/c, f_M = 1000 Hz; (d) Resonant regime: v_{in} ~ 30 m/c, f_M = 870 Hz

In the present study, we have numerically simulated the gas-dynamic structure of the swirling flow under experimental conditions described above and have proposed a simple model of the observed phenomena of acoustically induced transitions of CHFD discharge.

2 Mathematical modelling

2.1 Governing equations and boundary conditions

For modeling turbulent flow in this tube, we use the unsteady Reynolds averaged Navier-Stokes (URANS) equations which can be written in the form:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v_i)}{\partial x_i} = 0,$$

$$\frac{\partial(\rho v_i)}{\partial t} + \frac{\partial(\rho v_i v_j)}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j} - \frac{2}{3}\delta_{ij}\frac{\partial v_k}{\partial x_k}\right)\right] + \frac{\partial}{\partial x_i}\left[-\rho\overline{v'_i v'_j}\right] \qquad (1)$$

$$\frac{\partial(\rho E)}{\partial t}+\frac{\partial[v_i(\rho E+P)]}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\kappa+\frac{c_P\mu_t}{Pr_t}\right)\frac{\partial T}{\partial x_j}+v_i\left(\tau_{ij}\right)_{eff}\right]+\Im(\vec{x}),\ E=h-\frac{P}{\rho}+\frac{v^2}{2},\ P=\frac{\rho T}{M},$$

where $\left(\tau_{ij}\right)_{eff}=\mu_{eff}\left(\frac{\partial v_j}{\partial x_i}+\frac{\partial v_i}{\partial x_j}\right)-\frac{2}{3}\mu_{eff}\frac{\partial v_k}{\partial x_k}\delta_{ij}$ is the deviatoric stress tensor; $\left[-\rho\overline{v'_i v'_j}\right]$ is Reynolds stresses which must be modeled in order to close the set of equations, v_i, v'_i,, ρ, T P, E, and h are the mean and fluctuating velocity components, density, temperature, pressure, total energy, and enthalpy, respectively; $\Im$ is the energy source, μ, μ_t, μ_{eff} are the molecular, turbulent, and effective viscosity coefficients, respectively; c_p is the molar specific heat capacity at constant pressure; κ is the thermal conductivity coefficient; Pr_t is the turbulent Prandtl number.

We imposed no-slip velocity and fixed temperature conditions along all the tube walls and fixed mass flow conditions at the tube inlets. The inlet turbulent intensity is set to zero basing on the experimental data [1,6,7]. At the outlet, we impose the pressure outlet boundary condition with the static pressure equal to the atmosphere pressure. The total mass flow rate m_t was assumed to be constant.

2.2 Numerical procedure

The numerical simulation of the non-stationary 3D turbulent swirling flow was made using the ANSYS FLUENT 16.0 program package, which solves the governing equations using the finite volumes method. For spatial discretization of density, momentum, energy and turbulent quantities, a second-order upwind scheme is used. The diffusion terms are central-differenced and second-order accurate. The pressure values at the faces are interpolated by use of the second order scheme.

For transient terms, we use the fully implicit scheme of the second-order accuracy. As a pressure-velocity coupling scheme the SIMPLE method was used. The convergence was obtained when the residual reaches 10^{-6} for the energy equation and 10^{-4} for the continuity equation, the momentum equation, and the equations for turbulent quantities.

The computational grid consists of $5.36\cdot10^5$ hexahedral cells. The grid refinement from $5.36\cdot10^5$ to $1.21\cdot10^6$ did not significantly alter the time-averaged velocity profiles. The time step is $5\cdot10^{-5}$ sec, since it is appropriate to the time scale of the problem and using less values only led to the increase in the computational time.

Strategies for turbulence modelling and simulations have been discussed in [8]. In the case of recirculating highly turbulent swirl flows, Wegner et al. [9] compared URANS results with LES and experimental data and could prove good coincidence. In our simulations, the Spalart-Allmaras model with the enabled curvature correction option was used.

The action of an external acoustic field was simulated by adding a source term to the right side of Navier-Stokes equation (1) for the axial momentum component. The source term is a sinusoidal function of time with a given frequency and amplitude.

3 Results of numerical simulation and discussion

The results of numerical simulation demonstrate the presence of a left-handed stationary helical structure of the backflow in the near-axis zone of the tube. The near-wall region corresponds to a direct spiral flow. The typical flow helical structure obtained numerically is shown in Figure 3.

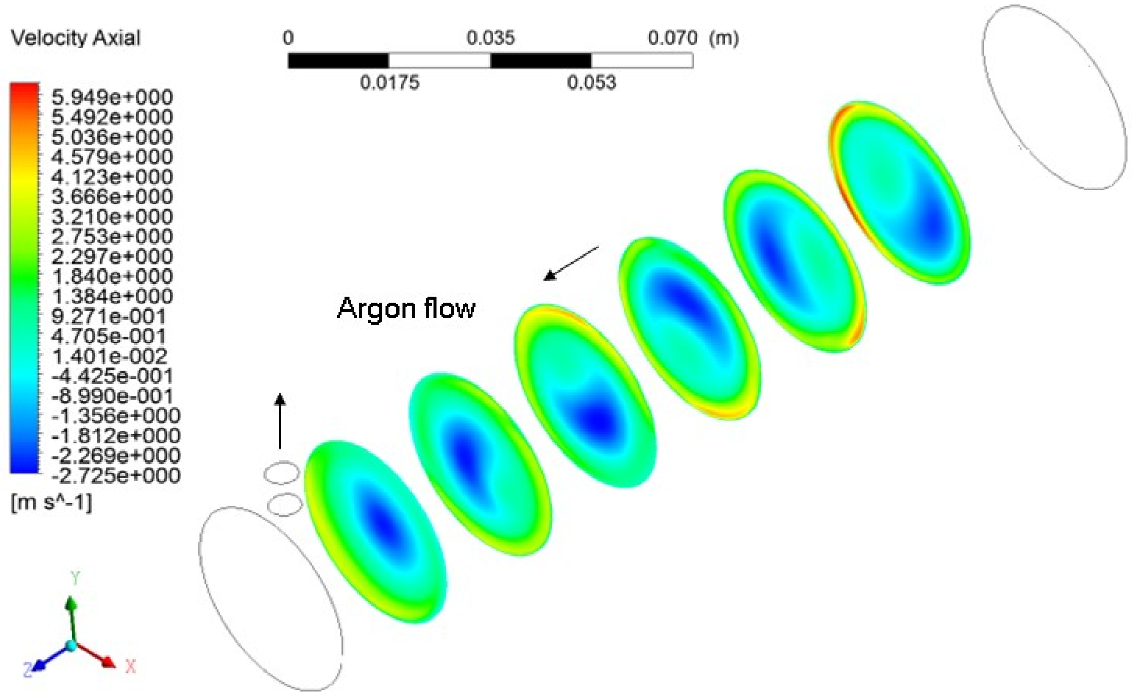


Figure 3: Axial velocity isolines in different cross-sections. The axial coordinate *z* increases right-to-left.

The trajectories of test particles injected into the flow in the vicinity of the duct axis near the outlet are shown in Figures 4 and 5. It is clearly seen that the particles initially move in the opposite flow direction from outlet to inlet, rotating around the inner helix, then they pass to the outer near-wall region and move to outlet. In the absence of the sound wave and in non-resonant mode the particle lines are homogeneously distributed along the duct wall, Figure 4, whereas in the resonant mode the majority of particles describes an almost similar path while moving toward the outlet. This path forms a new spiral structure in the near-wall region, Figure 5.

Comparing to the experimental results, one can suppose, that these spiral pathlines in an acoustic field produce a convective heat flux transferring heat from the hot inner discharge zone. The appearance of this flux leads to increase in the average ionization rate in the hot zones that leads to a significant drop in the resistance of the channel [3,10] and forms a new discharge channel, which shape follows the structure of the spiral flow. The form of the simulated large helical structure can be matched with the experimentally observed disturbances of the plasma filament in the swirling flow with an excited standing acoustic wave, Figure 6.

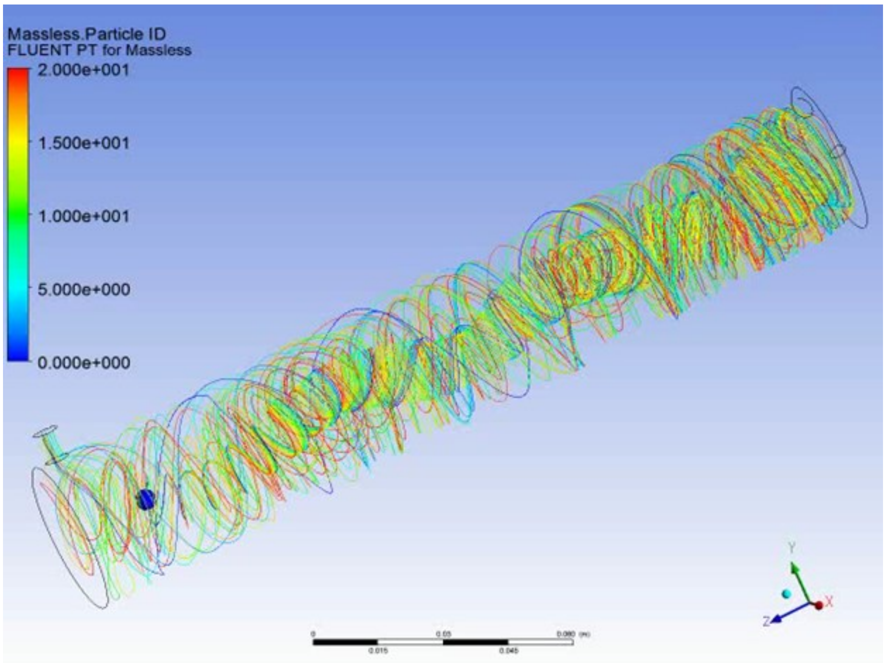


Figure 4: Particle trajectories in the absence of acoustic noise

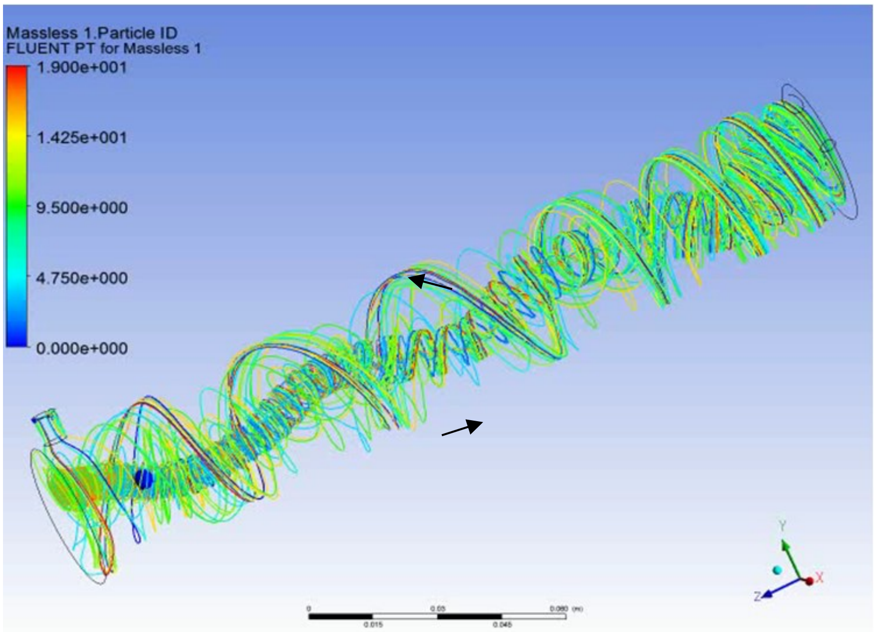


Figure 5: Particle trajectories in the presence of acoustic noise of resonant frequency f_S = 870 Hz. Acoustical Mach number M_S = 10^{-4}.

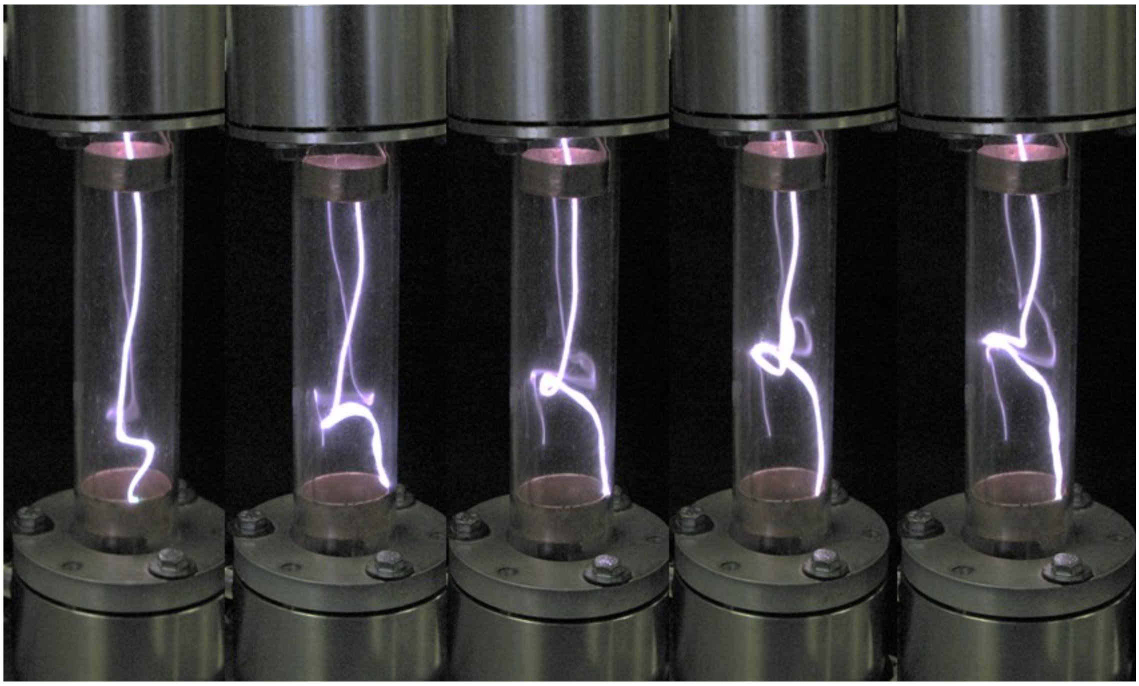


Figure 6: A longitudinal plasmoid created by the pulse repetitive capacity HF discharge in swirling flow observed at different time moments. Time *t* increases left-to-right, v_{tn} ~ 30 m/c, resonant regime f_M = 870 Hz.

4 Conclusions

In current work, a mechanism providing acoustically induced generation of experimentally observed helical disturbances on a plasma filament in swirling flows is presented. The simulation of the gas flow shows that the acoustic standing wave forms a new helical structure in the near-wall tube region due to the appearance of a particular spiral trajectory, which is followed by majority of test particles. In the flow with a gas discharge, this pathline is supposed to carry the heat flux from the inner near-axis zone of discharge to the outer near-wall flow region. The heating of the gas flow causes an increase in ionization rate and drop in channel resistance that leads to the formation of a new discharge channel taking the helical shape of the gas flow pathlines. The shape of the simulated helical structure in the near-wall region can be matched with the experimentally observed large-amplitude disturbances of the plasma filament in the swirling flow with an excited standing acoustic wave.

Acknowledgments

The study was supported in part by the Ministry of education and science of Russian Federation under Competitiveness Enhancement Program of SSAU for 2013-2020 years and by State assignment to educational and research institutions under projects 102, 608, GR 114091840046 and by RFBR under grant 14-02-97030 r_povolzh'e_a.

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