Numerical simulation of an argon swirling flow in the presence of a DC discharge

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Abstract. Numerical simulations of the non-stationary three-dimensional swirling Ar flow are presented for plasma vortex reactor (PVR) with a paraxial heat source at various positions of the heat source and electrode forms. Flow and duct parameters correspond to the experimental conditions. Flow velocity and thermal fields have been obtained.

1. Introduction

Swirling flows are known to be important for devices with heat release such as plasma dynamic systems [1], aero-engines [2,3], hydrogen plasma generators [4,5], etc. Recently, the problem of creating efficient compact energy sources, including alternative ones, has become increasingly noticeable [4,5]. One of the most promising technologies is the use of plasma vortex reactor (PVR), which can be both heat and hydrogen generator.

Intensive studies of a plasma chemical reactor started a few years ago [5-7]. Peculiar properties of gas-plasma and heat fluxes in the presence of longitudinal heterogeneous electric discharge in the swirl flow were studied in [6,7]. The test gases used in this setup are the following: argon, water vapor, aluminium nanoparticles, and their mixtures. It is shown that in the heterogeneous plasmoid formed in the argon-water vapor-nanoparticle mixture, UV-radiation and soft X-ray radiation are generated, whereas in the diffuse plasma produced during the discharge in pure argon or in the argon-nanoparticle mixture, this radiation is absent.

In addition, in a heterogeneous plasmoid there is a significant release of thermal energy ~ 1-2 keV per metal atom. It is shown that the coefficient of performance (COP) depends on the parameters of the vortex flow itself, the electric discharge and the used material. The energy cost of the hydrogen molecule production in the PVR has been estimated. It turns out to be much lower than the market price, due to the release of energy during the interaction of water vapor with excited nanoclusters of aluminium.

The efficiency of hydrogen and heat production obviously increases in the field of vortex flows, which transfer heat predominantly downstream. At the same time, the structure of the flow is strongly influenced by a number of factors: the organization of the input and output of the mixture components, the shape and arrangement of the discharge electrodes, swirl number and swirl rate, and the mass flow of components.
The self-consistent simulation of the flow structure is very complicated and requires joint modeling of the gas-dynamic and discharge subsystems. In this paper, as a starting step, a simulation of the structure of the gasdynamic and thermal fields formed in a three-dimensional unsteady viscous turbulent vortex flow of pure argon in a PVR duct under experimental conditions [6,7] is carried out for different configurations of electrodes system. The ultimate goal of investigation was to ascertain the effects of introducing electrodes into the flow: the geometry and positions of electrodes to minimize the upstream heat flux which leads to energy losses through dissipation by heating parts of the apparatus. The spatial distributions of the source power were chosen phenomenologically.

2. Mathematical modelling

2.1. Geometrical configurations, governing equations and boundary conditions

The schematic swirler and duct geometry is sketched in figure 1. The swirler has four tangential inlets with independent gas supply. The system of electrodes is only outlined. Its varying parameters are the shape and the distance from the swirler \( z_0 \). The heat source is located between two electrodes. The outlet of the duct has the form of a nozzle.

![Schematic diagram of the geometry of swirl generator and duct](image)

**Figure 1.** A schematic diagram of the geometry of swirl generator and duct used for numerical simulations, \( L=70 \text{ cm}, R=2.5 \text{ cm}, l_0=12.0 \text{ cm} \). Here \( R_0 \) is the electrode radius.

Standard unsteady Reynolds averaged Navier-Stokes (URANS) equations were used to describe the flow:

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

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

(1)

where \( \rho \) is the density of the gas, \( v_i, v_j \) are the mean and fluctuating velocity components, \( \rho \) is the density, \( P \) is the pressure, \( T \) is the temperature, \( E \) is the total energy, and \( h \) is the mean enthalpy, respectively; \( v_i' \) and \( v_j' \) are the mean and fluctuating velocity components, respectively; \( \rho \) is the density of the gas; \( \mu \) is the molecular viscosity; \( \mu_b \) is the turbulent viscosity; \( \mu_eff \) is the effective viscosity; \( \kappa \) is the thermal conductivity coefficient; \( \rho \) is the density of the gas; \( \mu_b \) is the turbulent Prandtl number.

The no-slip velocity and fixed temperature conditions were imposed along the tube and electrode surfaces. At the duct inlet and outlet, fixed mass flux conditions were used. The inlet turbulent intensity set to moderate values of 1-5% did not affect the flow structure discernibly. At the outlet, we imposed the boundary conditions with the static pressure equal to the atmosphere pressure.
2.2. Flow, heat source and electrodes parameters
In what follows, we investigate the problem for Ar close to the experimental conditions [6,7] corresponding to the total mass flux rate \( m = 2 \text{ g/sec} \), the homogeneous heat source power \( N = 50 \text{ W} \) and the gas pressure \( P = 1 \text{ Bar} \).

Three different types of electrodes are considered in the simulation: a sharp or plain ended thick electrode with a diameter \( D_0 = 2R_0 \) of 20 mm and a length of 40 mm, a sharp or plain ended thin electrode with a diameter \( D_0 \) of 5 mm and a length of 40 mm, and a pipe-like electrode with an external diameter of 20 mm and a thickness of 1 mm. The interelectrode distance \( l_0 = 12 \text{ cm} \) remains constant, whereas the position of the input electrode \( z_0 \) varies from 52 to 60 cm from the inlet. The heat capacity of the swirler, electrodes and nozzle elements, as well as the thermal conductivity of the walls were neglected in this simulation.

2.3. Numerical procedure
The numerical simulation of the non-stationary 3D turbulent swirling flow was made using the ANSYS FLUENT 15.0 program package, which solves governing equations using the finite volumes method. In our simulations, the Spalart-Allmaras model was used. A detailed analysis of the use of the turbulence models in similar problems is given in [1].

For spatial discretization of density, momentum, energy and turbulent quantities, a second-order upwind scheme is applied. The use of higher-order schemes has not changed the flow parameters considerably. The diffusion terms are central-differenced and second-order accurate. We interpolate the pressure values at the faces using the PRESTO! scheme because of the strong swirl nature of the flow.

For transient terms, we used the fully implicit scheme of the second-order accuracy. Different pressure-velocity coupling schemes were tested and gave equal results. So, we used the SIMPLE scheme as the least resource intensive. The convergence was obtained when the residual reached \( 10^{-6} \) for the energy equation and \( 10^{-3} \) for the continuity equation, the momentum equation, and the equations for turbulent quantities.

The computational grids consisted of about \( 4 \cdot 10^6 \) (from \( 3.7 \cdot 10^6 \) to \( 4.3 \cdot 10^6 \)) hexahedral cells. The grid refinement did not considerably alter the gasdynamic parameters. Calculations with different values of time step from \( 1 \cdot 10^{-4} \) sec to \( 1 \cdot 10^{-6} \) sec were carried out. Finally, the time step equal to \( 5 \cdot 10^{-5} \) sec was set since its lower values led only to an increase in the computational time.

3. Results of numerical simulation and discussion
The calculations have showed the following features of the formation of the flow velocity field and the thermal field.

To a great extent, the structure of the flow is determined by the paraxial counterflow zone, typical for strongly swirled flows [1]. Essentially, there are two types of such phenomena: bounded by the thick electrode (figure 2a, c) and faded away due to a gradual decrease of angular momentum of the fluid and a consequent fall of the swirl number below the critical value (figure 2b).

Working towards a design system with desirable behavior, we analyzed several cases. The first one is two thick cylindrical electrodes (figure 3 a-c). Such a pattern has a fundamental drawback: between the electrodes, a dead zone is formed where the pressure (figure 3a) and inertia forces almost prevent from the mass exchange with the outer flow (figure 3b). Eventually, it leads to the zone overheating (figure 3c) and makes the employed modelling approach inapplicable. The second case of thick and thin electrodes (figure 3 d-e) is roughly the same, with only slight progress. Structures of counterflow (figure 2a) and dead zones (figure 3a, b, d, e) in both setups have several common features. First and foremost, the thick electrode placed in the upstream position virtually stops the counterflow. No less important is the fact that the pressure between electrodes is lower than in peripheral areas, nevertheless it is higher than pressure downstream from the second electrode. Taking into account those facts, we proposed two configurations (figure 4). In the case of thick and pipe-like electrodes, the pressure gradient along the symmetry axis draws out the hot gas from the interelectrode area. In the fourth version, electrodes set position is downstream from the end of the counterflow zone.
Still, it is not possible to replace a pipe-like electrode with a solid one because, in that case, the counterflow zone prolongs (figure 2c), and heat is partly carried away upstream.

**Figure 2.** Typical structures of the counterflow zone. Only areas of negative velocity are shown.

**Figure 3.** Longitudinal fields of relative (to atmospheric) static pressure (a, d) (only values higher than 630 Pa are shown for clear visualization), axial velocity (b, e) and temperature (c, f). Thick electrodes
are of radius $R_0 = 1 \text{ cm}$, thin electrode is of radius $R_0 = 0.25 \text{ cm}$, upstream coordinate of electrodes set $z_0 = 48 \text{ cm}$.

![Image](image.png)

**Figure 4.** Longitudinal fields of relative (to atmospheric) static pressure (a, d) (only values higher than $630 \text{ Pa}$ are shown for clear visualization), axial velocity (b, e) and temperature (c, f). Thick electrodes are of radius $R_0 = 1 \text{ cm}$, thin electrode is of radius $R_0 = 0.1 \text{ cm}$, upstream coordinate of electrodes set $z_0 = 48 \text{ cm}$ (a, b, c) and $z_0 = 57 \text{ cm}$ (d, e, f).

4. Concluding remarks

The numerical modelling has demonstrated that it is possible to configure electrodes for the energy to be transferred mainly downstream from the interelectrode zone. It may be accomplished by the pipe-like electrode through which, in one case (figure 4a-c), areas of different pressures are connected. Pressure forces, created in this way, draw out the hot gas towards the exit nozzle. The second set (figure 4d-f) ensures the desirable behavior by placing the electrodes downstream from the counterflow zone. The pipe-like electrode is still crucial since the solid one creates an obstacle producing the negative axial pressure gradient and prolonging the counterflow zone.

A qualitative agreement between the results of the calculations and the experimental data for pure argon \[6,7\] has been obtained. The next step in the simulation of the PVR is the calculation for real mixtures of Al, H$_2$O, Ar, taking into account the plasma-chemical kinetics of the discharge mixture components as well as thermal characteristics of the experimental set up.

Acknowledgments

The study was supported in part by the Ministry of Education and Science of Russia under the public contract with educational and research institutions within the project 3.1158.2017 and by RFBR under grant 16-41-630591.

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