CFD analysis of pylon equipped by plasma module for combustion in supersonic airflow

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Abstract. Two new geometrical configurations of pylon equipped by plasma module for combustion in supersonic airflow were developed and discussed. This paper presents the results of three-dimensional CFD simulation of the flow around the pylon. The simulation was performed for two modifications of pylon and two possible geometries of set of three pylons. No fundamental difference was found between the two pylon geometries. It was shown that in one case of the installation of three pylons it provides continuous flow around the pylons, which should ensure stable operation of the plasma generator. In the second case of the arrangement of the pylons, the obtained flow structure promotes faster mixing of fuel with air; however, a significant separation zone is formed behind the pylons, which may impede the stable operation of the discharge.

1. Introduction

Plasma-assisted combustion in a supersonic airflow is one of most promising approaches to the creation of the scramjet engine [1-3]. Stable ignition and flame holding of hydrogen and ethylene into a supersonic airflow was obtained for cold flow conditions using elongated filiform Q-DC discharge located near wall of combustion chamber [4]. Later such approach based on plasma-assisted ignition of ethylene was applied for ignition and flame stabilization of liquid fuel into supersonic airflow at wide range of flow conditions [5]. At the same time the investigations devoted to the reduction of power impact of plasma system were performed. It was shown that increasing of distance between electrodes results in increase of discharge length and such long discharge loop could ignite the fuel instead of using the set of discharge loops and provide significant decrease of power consumption [6].

When fuel is injected from the wall and the discharge is located near the surface, it becomes necessary to use a large area of the ceramic insert in the combustion chamber to prevent undesirable breakdown of the discharge on the channel wall. One approach to solving this problem was considered in [4,7], where a rather short ceramic insert of a small area is used, and the discharge is moved out from the wall into the stream by fuel jet because of combining the fuel injector and the electrode to create a discharge. However, this approach has obvious limitations on the depth of penetration of fuel and discharge into the stream, which limits the real application of this approach with significant scaling of the combustion chamber. An alternative solution is to move discharge to the core of flow using extended electrodes [8] or combine a classic fuel supply pylon with a plasma module generating long plasma filaments behind the pylon. A similar approach was previously considered in [9], however, the pylon had a rather complicated design that limited opportunities of discharge application. In this work, we propose a new geometric configuration of a pylon that combines fuel injectors and
electrodes to create an extended electric discharge in a layer of mixing fuel and oxidizer. The configuration has significant potential for scaling and subsequent use in real combustion chambers.

2. Discussion of pylon geometry

In previous works devoted to a plasma-assisted combustion in the supersonic flow, the fuel injector was combined with an electrode located on the channel wall (Figure 1). In this case, the injection was perpendicular to the flow to detach the jet of fuel from the channel wall. The discharge occurs between the anode inside the nozzle and the metal wall, then it blows off downstream, and the long (~ 80 mm) current channel located 5-15 mm away from the wall is formed. This configuration allowed the discharge to operate directly inside the air-fuel mixing layer, which positively affected the intensification of the mixing [10, 11]. A significant drawback of such configuration is that the fuel jet penetration to the core of flow is limited, that limits the possible scaling of combustion chamber. To solve this problem and preserve the advantages of plasma ignition methods, it was proposed to use thin streamlined fuel pylons equipped by electrodes ensuring the localization of the discharge in the mixing layer of fuel and air.

![Figure 1. Discharge image over schlieren visualization of the flow field [11]: 1—supersonic airflow, 2—injecting gas, 3—injector combined with electrode, 4—Q-DC discharge, 5—disturbances in the gas jet, 6—oblique shock wave in front of the jet.](image)

The pylon geometry is a thin streamlined object that slightly obstructs the flow (Figure 2a). On the downstream side of pylon two fuel injectors are installed at the top (first) and in a middle part (second). Independent channels for fuel supply pass through the pylon from the bottom side to the injection holes. Two electrodes made of copper wire are located between injection points close to them. The anode connected to a high voltage supply was insulated by a ceramic insertion to prevent the breakdown of discharge to undesirable parts of pylon. We expect a breakdown of discharge by shortest way between two electrodes and after that blowing down by airflow and formation of U-shape of discharge channel with long longitudinal part of loop. Two variations of pylon were discussed – with upper and lower location of anode insulated by ceramic insert (see Figure 2b). The choice of the location of the electrodes relative to the injectors is not accidental; such position and shape of electrodes (presented in Figure 2a) should provide operation of the discharge in the area of mixing the fuel with the air flow. It should have a positive effect on mixing and ignition of fuel in the supersonic airflow. The influence of a discharge on gas dynamics around the pylon is not considered in this work and will be investigated in a next part of our research.
Figure 2. Pylon geometry: a) pylon, combining a plasma generator and the fuel injection. 1 - cathode, 2 - anode, 3 - ceramic part, 4 - fuel channels; b) a test section with two different pylons installed (in a section passing near the plane of symmetry).

3. Description of CFD model

The calculations were performed in the FlowVision 3.10.02 software package. Flow modeling was performed by solving a three-dimensional unsteady system of Navier-Stokes equations using the modified k-ε FlowVision turbulence model (URANS approach). No-slip boundary condition was considered on the walls and wall functions are used to model the boundary layer. The boundary condition "Total pressure" equal to atmospheric was set at the outlet of the calculation domain. The following velocity, static pressure and temperature were set at the inlet of the test section.

Boundary condition: $P_{at} = 67000$ Pa, $V = 885$ m/s, $T_g = 318$ K

Boundary condition for fuel injection (ethylene): $T_g = 300$ K, $G_m = 1$ g/s (average value for one injection hole). Deviations of fuel flow rate for each of the injectors were no more than 5% of the average value.

The calculation grid used in all simulations was rectangular. Initial grid consisted of large cells and local adaptation of grid applied. Manual adaptation consumed near the walls and the pylons, and inside the fuel supply channels. An automatic periodic adaptation of grid was used in the areas of high pressure and density gradients and areas containing ethylene and low Mach number values. Result of such complex grid adaptation is presented in Figure 3. This allowed us to simulate a three-dimensional flow in half of combustion chamber using no more than 5 million cells in each calculation. It is also possible to use this technique at conditions of unsteady flow arising for any reason by setting up automatic periodic rebuilding of the grid every few time steps or in time with a variable interval. As a result of adaptation, the computational grid provided $Y+$ values in the range from 60 to 100. It corresponds to 8 cells per injector diameter.

Figure 3. Adaptation of the computational grid to the solution. Oblique shocks are shown using a pressure gradient ($X$-component) and a mass fraction of ethylene in the range 0.1-1 is presented, visualizing the fuel jets.
4. Results and discussion

Two different geometries of set of three pylons were tested. Both of them contain two types of pylon (with upper and lower location of anode insulated by ceramic insert) at the same time: model with upper location of anode was installed in center and the second model was installed at the left and right sides. Symmetry condition was used at the central plan because of the geometry symmetry for reducing the number of cells and increasing the calculation speed. At the first set the pylons were located at lateral spacing of 24 mm (case №1) from the central pylon (distance between the centers of the pylons is indicated). Analyzing the data obtained during the simulation of the first geometry, it was noticed that the shock waves from the pylon fall on the walls of neighboring pylons, as it presented in Figure 4(left).

![Figure 4](image)

**Figure 4.** a) Mach number - side view and top view of the cross-section along the flow for the installation of pylons No. 1 (left) and No. 2 (right); b) the velocity vectors and the Mach number near the pylons for option No. 1 (left) and No. 2 (right).

It was proposed to arrange the pylons relative to each other than the shock wave from the central pylon falls into the area located directly behind the fuel injectors of neighboring pylons to further improve of fuel mixing with the air flow. This should lead to the development of hydrodynamic instability at the shear layer between the fuel and the oxidizer and accelerate the mixing. Therefore the side pylons were moved away from the central one, and a lateral spacing between pylons was set to 31 mm (case №2). As it is presented in Figure 4(right), this geometry transformation results in a necessary configuration of oblique shocks: when the shocks waves caused by the leading edges of the pylons do not interact with the walls of the neighboring pylons, but cross the jets of fuel.

But as a result of lateral spacing modification a much more extensive subsonic zone was formed behind all pylons. The Mach number M = 1 is shown in black color in Figure 4. Moreover, separation zone with a reverse flow was formed, which should negatively affect the discharge operation: it is assumed that after the breakdown, the discharge together with the fuel should blow downstream and
its transverse part of plasma channel should not locate near the ceramic part of the pylon. However, the reverse flow behind the pylon will prevent this. The absence of a separation zone in the first case of the set of the pylons can be explained by the fact that the supersonic flow passing through the oblique shock wave caused by the pylon deviates towards the neighboring (second) pylon, and in the stern zone of the second pylon the flow is almost co-directed with the surface of the pylon tail. This particularity results in uninterrupted flow near the pylon tail. In the second case the shock wave falls behind the pylon to the region of the jet injection, creating a region of increased pressure there and causing an increase of the separation zone.

On the other hand, the fuel jet has a large surface of interaction with the oxidizer in the second case and mixes faster with the flow, which is clearly seen from the visualization using three-dimensional isosurfaces of a fixed fuel mass fraction of 0.2 for both cases (Figure 5). In the second case mixing the jet with the airflow occurs earlier than in the case with a narrower arrangement of the fuel supply pylons. The jet has a classic structure in the first case: a pair vortex is formed, breaking each jet into two parts, which have a smaller diameter than in the second case, in which the passage of the jet through the separation zone facilitates the rapid expansion of the jet and mixing with air. The possibility of combining the advantages of these two cases is planned to be considered in the further analysis of the results. For example, installing only two pylons in side positions will allow the interaction of the shock wave of one pylon with the fuel jets of the other pylon significantly downstream from the pylon, which will improve mixing and will not lead to the formation of separation zones behind the pylons. Another approach is to increase the length of the electrodes and organize the discharge at a some distance from the pylon.

**Figure 5.** 3D shape of fuel jets at different pylon locations (No. 1 on the left, No. 2 on the right). An isosurface with a mass fraction of ethylene of 0.2 is shown.

### 5. Summary

Three-dimensional flow modeling was performed using prepared new three-dimensional models of pylons combined with plasma module. Simulation of two cases of pylons arrangement was performed: with a distance of 24 mm between the centers of the pylons and with a distance of 31 mm. It was shown that in the case of installing three pylons, a distance of 24 mm provides an uninterrupted flow around the pylons, which should ensure stable operation of the plasma generator. Uninterrupted flow will be ensured with a distance of not more than 25 mm between the pylons. The resulting flow structure promotes faster mixing of fuel with air flow at a distance of 31 mm between the pylons; however, a significant separation zone with reverse flow is formed behind the pylons, which may impede the stable operation of the discharge.

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