Investigation of synthetic jet magnetohydrodynamic actuator

P N Kazanskiy, I A Moralev, A V Efimov, A A Firsov and R E Karmatskiy
Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13
Bldg 2, Moscow 125412, Russia
E-mail: fokkoo@yandex.ru

Abstract. Current paper is devoted to study new plasma actuator type—plasma synthetic jet actuator, based on the magnetohydrodynamic flow acceleration. Gas is accelerated inside the planar channel by the pulsed arc with current ~ 300 A, moving in the external magnetic field of 1.2 T. The channel is opened at both sides. The asymmetric jet, formed at one of the channel ends is studied by means of shadow imaging and particle image velocimetry. The total thrust of the system is estimated by integrating velocity field and by direct measurement of the recoil force.

1. Introduction
The energy efficiency and energy saving plays a key role in the aviation transport sector and wind energy. Increase of various vehicles flight performance requires development of new flow control principles and actuators for their implementation. In the last two decades there is a splash in the scientific studies devoted to the plasma flow control. Main advantage of plasma actuators is that they operate directly with the gas, that lead to higher response times and simpler construction in comparison to the mechanical or fluidic devices. The overwhelming majority of the papers in plasma aerodynamics deals with actuators, based on the dielectric barrier and corona discharges [1]. However, the application of this type of discharges for direct flow control is limited to the low velocities (up to 20 m/s), due to the low thrust of the device (~ 80 mN/m of electrode length). Successive flow control at higher velocities was shown only for the systems, where the significant amplification of the initial disturbances occurs, such as shear layers [2, 3] or laminar boundary layers [4].

The actuators based on the effusion of the jet through the exit of the micronozzle, placed on the controlled surface, are used to control the flow at the wide range of the velocities, up to supersonic conditions [5]. In the case of the synthetic jet systems, no air supply is connected to the cavity. The pressure in the cavity is periodically altered and the actuator operation cycle consists of exhausting and refilling of the cavity by the same nozzle, therefore the average mass flux of the system is zero. Synthetic jets actuators were shown to attain higher performance, i.e. for the flow separation control [5], in comparison to the steady blowing systems.

The alternating pressure in the cavity is usually created by a mechanical piston (magnetically-driven diaphragm) [6], or by heating of the gas. In plasma synthetic jets actuators [7], pressure difference is created by heating of the gas inside the cavity by an electrical discharge pulse.
The efficiency of energy coupling, stored in the capacitor, towards to the mechanical energy of the exhausting jet is ruled by the matching of the impedance of the electrical circuit and the discharge channel. Therefore, one of the main ways of optimization for the pseudo synthetic jet (PSJ) actuators is increasing of the discharge length. It was also shown [8] that the reduction of the pulse duration down to nanosecond scales leads to the increase of the electric field in the discharge channel and therefore to the increase of the coupling efficiency of the actuator supply system.

Another existing problem in the development of the PSJ actuators is the duration of the induced momentum with the increase of the device operating frequency. This is caused by the fact that the pressure difference across the nozzle during the refilling stage of the operation cycle is limited by the pressure in the external flow.

The increase of the efficiency and peak characteristics of PSJ actuators can be provided by the usage of the magnetohydrodynamic (MHD) effect for gas acceleration inside the cavity. Application of the external magnetic field to the transverse arc channel can add a significant momentum to the actuator induced jet. Since the flow induced by electromagnetic force, in contrast to the one following thermal expansion, is anisotropic, the opposed edge of the discharge cavity can be open, thus increasing the mass flow during the refilling stage and the operation frequency of the device.

This paper is dedicated to the preliminary analysis of the actuator-induced jet.

2. Experimental setup and results

The design of the actuator is shown in figure 1. The cavity walls are formed by two flat parallel plates made of alumina ceramics, with the side gaps between them sealed by a silicon compound. The gap between the plates was varied in the range \( h = 1.7\)–3.7 mm. The tungsten electrodes were mounted along the walls of the lower plate surface channel. In order to stabilize the ignition point of the discharge the tips were formed at one end of the electrodes. The permanent magnetic field with a magnitude \( \sim 1.2 \) T was created in the gap by a pair of NdFeB magnets, placed close to the outer side of the plates.

The structure and parameters of the synthetic jet were studied by shadow imaging (shown in figure 2a) and particle image velocimetry (PIV; shown in figures 2b and 2c). On the shadow photographs one can clearly see symmetric weak shock waves, propagating after the breakdown from both channel ends. After \( 40 \) µs the breakdown the jet head is obtainable at one of the channel exits, the direction of the jet determined by the direction of the arc sweep through the channel. During the further evolution \( (530 \) µs) the vortex ring is formed, containing the heated gas from the cavity.

Measurement of the velocity field in the pulsed jet was made by PIV. The measurement results are shown in figures 2b and 2c. The discharge pulse leads to the formation of a vortex ring with flow velocity up to \( 540 \) m/s. The vortex size and propagation velocity coincide with the data obtained by Schlieren photography. During the further evolution, the vortex core increases its size, and the velocity magnitude in the core decreases. The attempt to estimate the thrust of the actuator by integration of the momentum across the jet was made. The calculation was performed as:

\[
p = \int_0^{0.005} \int_0^{0.001} mV(x, y) dx dy. \tag{1}
\]

It was assumed that the air density did not change and was \( 1.3 \) kg/m\(^3\). The structure of the jet was taken in 2D approximation. The thickness of jet was taken as \( 1 \) mm. The jet momentum increases up to the moment \( t = 170 \) µs to \( 4.5 \times 10^{-4} \) kg m/s. Then during \( 300 \) µs the total momentum reduces more than twice in comparison with the maximum value.

The evolution of the jet head velocity \( V_h \) with time is shown in figure 3. Maximum magnitude of \( V_h \) depends on the arc current amplitude, and relatively independent on the thickness of the
Figure 1. Scheme of the synthetic jet MHD actuator: 1—electrode, 2—the arc, 3—side wall, 4—permanent magnet, 5, 6 upper and lower ceramic plates.

Figure 2. Schlieren photography of MHD actuated jet after 50 µs discharge ignition, front view (left). PIV flow visualization near the nozzle, front view (in the middle). PIV flow visualization near the nozzle, side view (right).

channel. Maximum velocity was obtained to be as high as 200 m/s, with a reduction time of about 160 µs. The jet penetration depth in the atmospheric air conditions was found to be 16–23 mm.

The actuator was powered by the bell-shaped current pulse with an amplitude of 300 A and base duration 150–300 µs. The pulse was formed by discharging the capacitance of 2–10 µF through the inductive load, with the thyratron used as a switch.

After the breakdown, the average voltage drop across the discharge gap was 150 V, with clearly obtainable oscillations in the range 100–170 V. These oscillations occur due to a stepwise manner of the arc movement along the electrodes, especially at the cathode. The average discharge pulse power was 11 kW, corresponding to electric discharge energy per pulse $\sim 3.3$ J. Estimated energy loss of the supply capacity is 16 J. Dimension of the channel was $60 \times 8 \times 1.7$ mm$^3$. The volume of synthetic jet actuator cavity was 816 mm$^3$. It corresponds to $10^{-3}$ kg of air at standard conditions for temperature and pressure.
The dimensionless energy input coefficient can be defined as:

$$\varepsilon = \frac{0.5CU^2}{c_v \rho_0 V_0 T_0} = \frac{3.3[J]}{0.7 \times 10^4[J/kg/K] \times 1.3[kg/m^3] \times 0.8 \times 10^{-6}[m^3] \times 293[K]} = 15.5. \quad (2)$$

The dimensionless energy input and generated velocity, obtained for the MHD actuator are comparable to the parameters of a classical PSJ system [7]. It means that the efficiency of gas acceleration in the MHD system is at least as effective as in PSJ actuators. However, the operation frequency of the system will be higher due to the absence of the nozzle and higher refilling rate of the discharge chamber.

The density of the gas was not measured in current paper. So the analysis of jet momentum from PIV data can give high measuring error. Another pulse measurement method was carried out. The direct measurement of total jet momentum was organized using by estimating the recoil force on the magnets and channel walls. Plasma actuator was mounted on the pendulum, and the maximal deflection angle of the thread was measured after the discharge pulse. The
small angle was measured by tracing the reflected laser beam from the surface of the actuator system.

Thrust of the actuator as a function of the discharge current is shown in figure 4. It can be seen that the momentum increases at $I \sim 80$ A up to the value $\sim 10^{-4}$ kg m/s$^2$. At higher current the arc comes out of the channel and further current increase does not significantly affect the pulse. One can see that the total recoil momentum is greater in the comparison to the velocity-based total thrust values, which comes from the fact that density variations in the jet are not taken into account for the latter case.

3. Conclusion

The new plasma actuator type was designed. This plasma synthetic jet actuator is based on the MHD flow acceleration. It was shown that current plasma actuator forms jet of heated air. The PIV shows that the actuator forms a vortex ring with flow velocity up to 540 m/s. The velocity of the gas can reach up to 200 m/s. The pulse of the jet was measured by two independent methods (PIV system and pendulum). It has been found that the pulse of the jet can come up to $10^{-4}$ kg m/s. The efficiency of MHD plasma actuator is close to efficiency of other mechanic and heating actuators. Nevertheless the construction of MHD plasma actuator has additional nozzle for gas suction. This type of actuator seems promising in increasing the pulse jet repetitions.

Acknowledgments

The work was performed with the financial support by the Russian Science Foundation grant No. 14-50-00124.

References

[1] Moralev I, Boytsov S, Kazansky P and Bityurin V 2014 Exp. Fluids 55 1–4
[2] Bityurin V, Efimov A, Kazanskiy P, Klimov A and Moralev I 2014 High Temp. 52 483–489
[3] Kazanskyi P, Klimov A and Moralev I 2012 High Temp. 50 323–330
[4] Kopiev V, Belyaev I, Zaytsev M, Kazansky P, Kopiev V and Moralev I 2015 Acoust. Phys. 61 178–180
[5] Jin D, Cui W, Li Y, Li F, Jia M, Sun Q and Zhang B 2015 Chin. J. Aeronaut. 28 66–76
[6] Gimeno L, Talbi A, Viard R, Merlen A, Pernod P and Preobrazhensky V 2010 J. Micromech. Microeng. 20 075004
[7] Zong H h, Cui W, Wu Y, Zhang Z b, Liang H, Jia M and Li Y h 2015 Sens. Actuators, A 222 114–121
[8] Zhu Y, Wu Y, Jia M, Liang H, Li J and Li Y 2015 Plasma Sources Sci. Technol. 24 15007–15019