Study of the geometry effect of the channel with variable cross section under forming transonic region in the supersonic flow with energy supply

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Abstract. This work concerns the process of deceleration of supersonic flow up to the transonic velocities in the channel. This process is connected with the problem of combustion organizing of fuels in the various ramjet engines. The influence of mode of energy supply and the type of channel geometry (axisymmetric or planar channel) is studied as well as the other factors. The similarity of gas dynamic structure formed under hydrogen burning and under pulse periodic energy supply is studied.

1. Introduction
One of the actual problems concerning organization of fuels combustion in various ramjet engines is decreasing of sizes of device. Especially it concerns the cases when it is necessary to organize combustion in the supersonic flow, because the size of a device increases simultaneously with the Mach number.

The simplified model for investigation of the main features of this problem is a channel with an increasing cross section. The energy is supplied into various zones of this channel. The formulation of the problem can be different. One of them is based on the Euler equations with simple function of heat release. The other variants of models analyze chemical kinetics and gas-dynamic basing on the Navier–Stocks equations. One of the combustion organization ways in such a system is described below. It is supposed that the channel includes two sufficiently long parts with the transversal section of constant area. The first of them is used to decrease the rate of flow up to the value almost equal to the sound velocity, but higher than it is. The amount of fuel which is supplied into this section is comparatively small. It is supposed that the main part of the fuel must be supplied into the expanding part of the channel located after the considered part of the channel with constant area. The scheme of such device is shown in Figure 1. It was described in [1]. The jet of compressed air is supplied transversely to the flow from the hole in the channel wall. The jet creates the effect of throttle. Moreover, it is creates a weak shock wave. By such a manner, the flow velocity decreases, and the ignition of fuel takes place in the front of the shock wave, and the process of burning begins to move upstream.
There are many difficulties of organizing such a process. This work is devoted to the study of the process in the first part of channel with constant area. The main aim is controlling the flow to create the stable transonic region in the sufficiently large region.

The main questions to be answered to solve this problem are the following: where the main part of energy must be supplied; what is the value of the average power; what are the main properties of the mode of the energy supplying which are characterized by the maximal effectiveness, and how long the process of the energy supply can continued. It is very important to avoid locking the channel: the amount of the energy must depend on the pressure in the channel. When the pressure increases sufficiently to lock the channel, the supply of energy must be finished. It is realized by means of the transversal jet. The value of pressure in the gas generator must be lower than the pressure corresponding to the channel locking. The channel is characterized by planar or by axisymmetric geometry. The axisymmetric geometry has advantages in the durability. So, it is important to determine if the conclusions for the planar channel can be used for the axisymmetric channel.

We concern only a part of questions in this work. Using the parametrical study based on the unsteady Euler equations and impulse periodic energy supply we estimated the average power which is necessary to decelerate the flow. It is necessary to consider a question about quantity of gas-dynamic pulses for creating a zone of transonic velocities. Nevertheless, the solution of the Navier – Stokes equations closed by the SST k-ω turbulence model with a simple kinetic model of hydrogen burning is also used to represent the common features of this process. The purpose of our work is restricted by clearing up some important aspects of the problem. The other purpose is to offer some possible ways to solve the problem considered.

2. The results of the parametrical study based on the unsteady Euler equations

2.1. The formulation of the inviscid problem
This formulation is based on the unsteady two-dimensional Euler equations. This formulation of the problem is described in more detail in [2, 3]. The planar or axisymmetric channel is under consideration. The area of the transversal section grows simultaneously with coordinate $x$ along the channel. As it was mentioned above, the channel contains two parts with the constant area of the transversal section. In the first part the Mach number is about $M=2$. This part contains the energy supply sources working in a pulse-periodic mode. These zones are located near the wall of channel. The jet of compressed air is also supplied into this part of channel. The system studied is schematically presented in the upper part of Figure 2a and Figure 2c.
The system studied and the Mach distribution: (a,c) – the Mach number distribution in the planar and axisymmetric channel respectively; (b,d) – the Mach Number which is averaged over the transversal section in dependence on the longitudinal coordinate $x$ in the planar and axisymmetric channel respectively.

The maximum frequency of the energy supply is so high that every portion of gas receives energy when travelling through the energy zones. The minimum frequency of the energy supply is determined by the condition when the portion of gas which received the energy in the previous period did not leave the channel until the next energy supply.

This simple model can be considered for energy supply by the plasma actuators. However, this model could be used for any process, when energy release in such a mode takes place.

2.2. The transonic area in the channel for axisymmetric and planar case

The transonic area in our case corresponds to the Mach number into the range $0.7<M<1.4$. This mode can be created for the channel of planar geometry as well as for the axisymmetric channel. The Mach number averaged over the transversal section, as the function of the longitudinal coordinate $x$, is shown for the planar geometry in Figure 2b and for the axisymmetric geometry in Figure 2d. The fragments of corresponding distributions of the Mach number are presented in Figure 2a and Figure 2c for the planar or axisymmetric case respectively. The energy supplied is equal to the energy realized...
during burning of the poor hydrogen-air mixture with the excess-air coefficient equal approximately to 10.

In such a way, we can see that formation of the transonic region is possible for axisymmetric geometry as well as for planar geometry of the channel.

The difficulty of creating stable transonic region is the following: the transonic mode is not stable in common case. A little disturbance is enough to convert it into subsonic mode. The jet of compressed air is used for solving this problem. This jet flows from the gas generator at the pressure equal to the pressure arising when maximum energy is supplied into the channel. By the way, when the pressure in channel is equal to the pressure in gas generator, the injecting of compressed air is stopped. But with decreasing of pressure in the channel the compressed air begins to flow to the channel again. These correlations we can see in Figure 3a.

![Figure 3](image)

**Figure 3.** (a) – dynamics of the jet consumption $m$ (curve 1) and pressure $p$ (curve 2) at the point close to the jet aperture; (b) – the coordinate of disturbance with respect of time.

The pressure in the channel in the region of the jet and consumption of compressed air as the functions of time are presented in Figure 3a. Moreover, increasing of pressure must decelerate the flow and aids in ignition process as it is described in [1].

Moreover, the existence of the jet sufficiently decelerates the upstream motion of disturbance. Let us consider the following dependence for the system which is similar to the system in Figure 2a. For numerical simulation, we consider the coordinate of pressure change on the some sufficiently great value within one grid cell as a coordinate of disturbance. We can observe the coordinate of disturbance for a long time corresponding to more than one gas dynamic pulses of compressed air. The sizes of the system are mentioned below. Let us consider the planar channel with size of about 30 mm and the total length of 500 mm. The total period of gas dynamic impulse consists of 30 msec. The time for maximal pressure in the gas generator (2 atm) is about 15 ms, and the time for the atmospheric pressure is 15 ms. The power of energy supply was proportional to the pressure in the gas generator. The intensity of energy supply is equal to the heat release during the burning of the poor air-hydrogen mixture with the excess air ratio 2.8 at the temperature 1000 K. In Figure 3b we can observe this time dependence. As we can see from Figure 3b, the disturbance upstream motion is sufficiently slower than the downstream one.
2.3. The range of power for the transonic area

There are three cases of the shock wave structure formation during energy supply. The first of them corresponds to reconstruction of the steady solution between the pulses of energy. This reconstruction takes place upstream the energy supply. The second of them corresponds to the case of locking of the channel when the shock wave moves to the narrowing part of the channel. The other case is characterized by the following properties: the disturbance change its position but remains in the part of channel with cross section constant area. We named the range of the power between the mode of locking and the mode of reconstruction as corridor of transonic regime. This corridor as function of period of energy supply is presented in Figure 4.

![Figure 4](image_url)

*Figure 4.* The chart is "normalized power N" – "period $\Delta t$ of the energy supply".

The upper corridor (the lines 1, 2) corresponds to the case of transversal energy supply. The dashed corridor and point-dashed corridor correspond to the analytical estimation for the transversal and surface energy supply respectively. The yellow corridor corresponds to the axisymmetric channel with the annular jet. The shaded region corresponds to planar channel. The axisymmetric channel is equal to the planar channel according to the sections area and to their length. We can see that both corridors are in the same range of parameters but the corridor for the axisymmetric channel is narrower. Moreover, the power corresponding to the transonic corridor for transversal energy sources exceeds twice the power for the near-wall sources with jet.

3. The results of the calculation based on the unsteady Navier-Stokes equations closed by the turbulence model

3.1. The separation zone near the jet

The CFD simulation based on the two-dimensional unsteady Navier – Stokes equations closed by the SST turbulence model was performed for the planar channel with jet without heat release (the transversal size of the section of constant area is 30 mm). The flow after the channel travels to the receiver with low pressure. The flow in the channel was formed under the pressure of about 3 atm in the prechamber. The jet of compressed air is formed under the pressure of 2 atm. The flow in the inlet is characterized by the turbulence intensity of 0.025% and turbulence length scale of 0.00025 m. The numerical scheme of the third order with using high-order term relaxation is used. The distribution of density is presented in Figure 5 at the beginning of jet injection (the time from the injection beginning is about 700 $\mu$s).
There is a sufficiently large separation zone near the jet. Figure 6 shows the experimental results of the authors [4]. In [4] the supersonic flow and flux from the pulse detonator (PD) with hole of compact shape are formed under the similar conditions: the Mach number in the flow is equal to 2 and the pressure in the PD is 2 atm (the time 1500 μs corresponds to the value of pressure into PD of 2 atm). The temperature of flow and jet is differs from the case of our numerical simulation. The transversal size in [4] is 136 mm, i.e. is fourfold larger than the transversal size in our case. The common view of Figure 5 and Figure 6 is qualitatively similar. In our case the separation zone is larger than that in [4], because we have a long gap in comparison with a small zone of compact shape. The jet diameter in [4] is 4.8 mm in comparison with transversal size of gap of 2 mm. It should be noted that the separation zones play the important role in the process of ignition and combustion.

**Figure 5.** Density distribution for the channel from Figure 2a.

![Density distribution](image)

**Figure 6.** The experimental results of the authors [4] for the supersonic flow with the Mach number M=2 and the compact flux produced by the pulse detonator (PD).

### 3.2. Numerical simulation of the hydrogen combustion

The burning of homogeneous air-hydrogen mixture when injecting jet is simulated in [5], the other similar systems were considered in [6, 7]. The results of the CFD simulation based on the two-dimensional unsteady Navier – Stokes equations is presented. The SST k-ω turbulence model is used. The planar channel with the same parameters as in the case from Figure 5 is considered. The hydrogen flows at the beginning of the constant cross section. The parameters of turbulence were changed: the turbulence intensity was 0.1% and turbulence length scale was 0.001 m. The process of burning is very complex and sometimes may be followed by special effects [8, 9]. Here the burning is modeled by one reaction for the qualitative analysis. Hydrogen flows through the holes into the channel wall. These holes were located opposite to each other. The Mach number distribution is presented in Figure 7. This distribution is qualitatively similar to the results [7] and to the case with a pulse periodic energy supply (Figure 2). These results of burning are similar to the ones of impulse-periodic energy supply. For this reason some conclusions concerning the case with impulse-periodic energy supply can be applied for the case of burning.
4. Conclusion

The data analysis indicates the following dependences which can be useful to organize the process of fuel combustion in the supersonic flow at M=2 in the channel. The near-wall energy supply is more effective for the planar channel as well as for the axisymmetric one. Injecting compressed air at the appropriate pressure of the gas generator helps to increase the time of channel locking. There is a quality similarity in the gas dynamic structure between the near-wall burning and the pulse periodic near-wall energy supply when injecting compressed air. So, the majority of conclusions for pulse periodic energy supply can be applied in the case of burning at the following condition: there must be approximate equality between the value of transversal length of hydrogen flux and the similar size for the zone of energy supply.

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