Calculations of shock-wave flow structure in axisymmetric channel with near-wall ethylene burning with throttle air jet

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\textbf{Abstract.} The CFD modelling of the ramjet start with low losses of the stagnation pressure was carried out. The basic feature of this start technology was the jet of compressed air creating effect of a throttle which aids in preliminary decelerating of the flow up to transonic velocities. The comparison with experiment was performed for the hydrogen burning. We studied the axial and near-wall supply of gas fuel. The physical mechanisms stimulating stable presence of transonic mode in the part with constant section were investigated within the frameworks URANS approach. It was shown that fuel supply blockage is a way to control near-wall supplying of gaseous fuel at considerably low pressure falls. And blocking the ignition processes is a way to control the axial supply at quite high pressure falls.

\textbf{1. Introduction}

Gas jet efflux is widely used to control the process of burning, including the methods to intensify burning in the ramjet combustion chambers at high flight Mach numbers [1-8]. The quality of mixing and minimizing the losses of full pressure are of special importance, but the stability of the process is important too. The works [1, 2] suggest the method to initiate operation of the ramjet combustion chamber. This method is a way to form the transonic range in the parts with constant section. The transonic mode is naturally unstable. So, here is the risk to realize the process of locking the channel. For this reason, of great importance is analyzing the factors that eventually could make the burning stable are of great importance.

The process of burning intensification [1, 2] is based on the interaction of gas mixture (non-mixed previously) with shock-wave structure produced by the throttle air-jet. One of the problem associated with the burning initiation method are selection of injector location and the its shape to supply the gas fuel. We showed that the near-wall burning of hydrogen supplied at low pressure through the wall [3] results in considerably high amplitude of parameters pulsation. It is caused by practically full blockage of fuel inflow by the zone of high pressure near the fuel aperture. On one hand, this mechanism results in to higher pulsations, on the other hand it prevents penetrating ample amount of fuel into the channel, which could cause the lockage of the channel. The numerical study represented in [3] showed...
that in case of axisymmetric supersonic supply of ethylene throw the injector with big diameter, the average amplitude of the pulsations parameters is quite low. The present investigation aims at obtaining physical parameters stabilizing the burning process in the system analogic to [1, 2] for near-wall and axisymmetric fuel supply. In spite of observing axial fuel supply, the process of burning can be considered as the “near-wall”, because the shock wave from the throttle jet supplied through the wall plays an important role. In case of considerably big diameters of the channel and fuel supply along the axis, burning initiation is not possible. The comparison was done for ethylene burning. The numerical modeling was done within URANS approach. The problem formulation for numerical modeling and its objectivation are represented in [3] (Reynolds averaged Navier – Stokes equations, (k-ε and SST k-ω turbulence modules). The same work describes the geometrical dimension of the system and the values of physical parameters of the system modeled (the initial condition is supersonic flow with Mach number M=2 in the part with constant section). Three variants to initiate burning in the channel are considered for axisymmetric supply of ethylene. These examples show that the process of locking channel can be prevented by three physical mechanisms: the same one of pressure difference change due to burning, that in the case of supplying through the wall, weak mixing processes, and limiting the consumption of inflowing fuel by the injector shape.

1. Comparison with experiment data

Quite detailed description of the experiment being compared in order to verify the methods chosen for numerical modeling is represented in [1-3].

The pressure distribution obtained numerically along the length of the flat or axisymmetric channel was compared to the experimental distribution [2] for the channels with the same cross dimensions. The region between the jet supplying hydrogen and the throttling jet in numerical simulation was somewhat shorter, so we make a comparison only in this area. The frequency of 10 Hz corresponded to the time interval of 100 ms, the gas flies at least 30 m, or 60 channel lengths during this time. Therefore, in a numerical simulation for 10 ms after the start of the gas-dynamic pulse, the effect can be considered as at constant pressure in the gas tanks.

As mentioned above, the combustion mode was pulsating. The curve 1 in Figure 2(a,b) shows the dependence of the static pressure on the coordinate along the channel for the flat and axisymmetric channel respectively. The pressure and the Mach number were obtained along the line outstanding 10 mm from the lower wall of the channel. The results [2] corresponding to the prechamber pressure 7 atm were presented in this figure by the curves2. The Mach number obtained by numerical simulation presented by the curves 3, and the lines 4 corresponds to the level of Mach number M = 1. One can see that there are pulsating transonic mode with a Mach number value which is approximately equal to M =1 for both of cases (flat and axisymmetric channel). In the flat channel (Figure 2(a)) the minimum value of the Mach number is 0.8, the maximum is 1.5 and average value is approximately M = 1.2. In the axisymmetric channel (Figure 2(b)) the minimum value of the Mach number is 0.5, the maximum is 1.5 for the flat channel and average value is approximately M = 1.

The average value of the Mach number in the flat channel is more than in the axisymmetric one. The reason is the difference in the square area of the slot zone. A throttling jet acts on the subsonic flow similar to the Laval nozzle, which results in flow accelerating again to the supersonic speed. The pressure ranges corresponding to the experiment overlaps with pressure range obtained numerically, but the average pressure level in the experiment is lower than in the calculation. It can be seen from the comparison of numerical simulation and experimental data that when the pressure in the channel increases (curve 1) the Mach number decreases (curve 3) and vice versa. The range of experimental pressures intersects with the calculated range, but on average, the experimental values are approximately the same for the case of the flat channel and are smaller for the axisymmetric channel. One can conclude that the flow regime in [2] is also transonic, but the values of Mach numbers are greater than M=1 and approximately equal to the M=1.2. The pressure level and its decrease at the end of the channel part with constant section are similar in the calculation and experiment.
Figure 2. The distributions of pressure calculated (curve 1) and experimental (curve 2) pressure distributions. Mach number distribution (curve 3), line 4 indicates level M = 1; a, b – hydrogen burning in the flat and axisymmetric channel respectively.

2. The axial and near-wall fuel supply comparison

For axisymmetric fuel supplying we studied three variants (the fuel temperature always was 300K). In the first case ethylene was supplied from the injector with inner diameter 10 mm at pressure 6 atm in the gas-generator. The ethylene consumption was so high, that if all ethylene supplied was burned, the channel would be blocked inevitably. No burning was observed in case of absence of throttle jet burning. When supplying the throttle jet a shock wave arose initiating burning in the circular zone close to the zone of oxygen contact with ethylene. No intensive gas motion along the radius was observed. Due to bad mixing, the biggest part of ethylene near the radius was not involved into burning process. The perturbation was moving upstream up to the injector hole. However, the channel was not locked, because the throttling jet formed Laval gas-dynamic nozzle. Near the throttling jet the pressure value was fluctuating close to the pressure level in the gas-generator. Here we could observe the manifestation of the same physical mechanism as in the case of near-wall fuel jet but in relation to the drossel jet. When much heat is generated, the pressure arises, and the throttling jet stops outflowing.

Figure 3. Temperature distribution at the beginning of process and in the quasi-stationary solution.

Absence of the throttling jet resulted in reducing burning intensity. The heat extraction was reduced; the pressure in the channel was lowered. But thank to this, the throttling jet could outflow again. And it initiated consequently the burning process. As a result, the transonic flow (M~0.7-0.8) was formed in the circular zone. Weak oscillations were observed. The flow reached supersonic velocity due to gas-dynamic Laval nozzle created by the throttle-jet. The Fig. 3a and 3b show the distribution of temperature at the ignition and end of the process. Burning continued in the expanding part of the channel.

In the second studied case homogenous mixture of ethylene-oxygen was supplied to the channel at the beginning of the process. Then, after the ignition was initiated when the mixture met the throttling jet, pure ethylene was supplied as in the first variant. This process is pictured in Fig.4. Starting from t = 3.34, pure ethylene was supplied from the output of the injector in order to prevent lockage of the
channel. As in the first case, we didn’t observe burning before the throttling jet contacted the shock wave. But in case of contact with throttling jet intensive burning arose with intensive gas turbulence, which is shown in Fig. 5-12. The, when proceeding to pure ethylene the process character became the same as in the first case studied.
In the third case, we studied flowing of pure ethylene from the injector with small inner diameter 1.8 mm, and external diameter 10 mm. The pressure in gas generator was about 15 atm, but thanks to small inner diameter the ethylene consumption was considerably low. Due to the big external diameter near the injector output the vortex zones were formed, which was resulted by ethylene going downstream mixed well with air. There was not burning before meeting the shock wave from the throttle jet. When the mixture contacted the shock wave, the process character was similar to the case with oxygen-ethylene mixture; considerable temperature non-uniformities were formed in transversal direction. These non-uniformities lasted during all the process. The Fig.5 represents two time points at the beginning of the process. The physical mechanism of process control (connected to the pressure difference between the gas generator of throttling jet and main stream in the channel) was acting here too. The inflow of ethylene into the channel was limited by the small inner injector diameter. Let us note, that in all three cases of axisymmetric supply the fuel consumption at the injectior output didn’t change considerably.

**Figure 4.** The time evolution of 2D temperature distribution for the axial ethylene supply: $t(t\text{(ms)}= 2.14, 2 - 2.17, 3 - 2.25, 4 - 2.43, 5 - 2.58, 6 - 2.76, 7 - 2.88, 8 - 2.98, 9 - 3.07, 10 - 3.22, 11 - 3.34, 12 - 3.48, 13 - 3.74, 14 - 4.01, 15 - 4.78, 16 - 5.36$

**Figure 5.** Temperature distribution for the case for injector with small inner diameter: $a - t(t\text{(ms)} = 2.14, b - 2.17$.

### 3. Conclusion

The comparison of the experiment and numerical data was performed for the case of the hydrogen burning for near-wall fuel supply for the flat and axisymmetric channel. The satisfactory coincidence of the numerical and experimental results was observed. It is shown that the ignition occurs due the interaction of shock wave from the throttle jet with fuel mixture, in spite of supplying method, disposition, and injector shape. In case of near-wall supply the heat extraction is limited due to blocking fuel inflow. In case of axisymmetric supply the heat extraction is limited by blockage of ignition processes. The scale of transversal temperature non-uniformities and other parameters rises sharply with increasing mixing degree of ethylene and air. The process of locking can be prevented by limiting fuel consumption or by low level of mixing. Nevertheless, in all cases the transonic mode is formed.

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