# Ignition and Flameholding of Hydrocarbon Fuels in High-Speed Flow.

**M. Goldfeld**,

*Institute of Theoretical and Applied Mechanics, 4/1 Institutskaya Str, Novosibirsk, 630090, Russia*

The complexity of the flow structure in supersonic flow does not allow carrying out a full theoretical calculation of the mixing, ignition and combustion of various fuels under diverse conditions. In spite of numerous investigations, so far there is no universal theory, which would explain the mechanism of the flame stabilization by the flameholders of different shape, which form the flows with recirculation regions. When solving a task of the flame stabilization, one should equally keep in mind both the flow structure behind a badly-flowed body, and the kinetics of a chemical reaction of different fuels.

In the work different methods of ignition and stabilization of combustion at supersonic speeds under different flow parameters (Mach number, pressure, total temperature, fuel-air equivalence ratio) and the stabilization conditions (cavity, back step, fuel injection position) were studied. Kerosene and gaseous propane were used as a fuel. The main purposes of the investigation were the following: (a) the definition of the conditions of the kerosene ignition with different flameholders form; (b) the study of the effect of different ways of fuel injection on the ignition efficacy; (c) the comparison of effectiveness of ignition and stabilization of liquid and gaseous fuels; (d) analysis of self-ignition and flame spreading processes in a supersonic combustor.

**Facility and model.** Investigations were carried out on connected pipe mode. First prechmaber of hot shot wind tunnel IT-302M was used as a source of hot gas. Such approach allows one to get a high-enthalpy flow with high pressure and temperature at the combustor entrance. The combustion chamber had a three-dimensional configuration with the solid and discrete cavity. The channel dimensions are 100×100 mm on the injector exit, including a step of 25 mm height from the top and bottom walls. The number of injectors amounts to four. A particular feature of the construction is the possibility of fast and convenient changes of injectors, variation of the Mach number and other conditions of the experiment. The special holes in the insulator and injector section were made and a fuel supply system was developed in order to supply fuel into separation zone/shear layer after injectors and into the boundary layer before the injector ramps.

During the tests the following parameters were measured: the total flow parameters in first and second prechambers; air and fuel flow rates; distributions of static pressure and heat flux in the model channel; Pitot pressure and temperature at model exit; base pressure distribution on the back step of injector device and on the forward/backward wall of the cavity post; flow visualization in CH and OH-radicals and in visible range. Large amount of measured stations (more than 120) allowed us to obtain detailed distributions of static pressure and heat flux including transversal directions and base pressure.

**Results and Discussion.** Comparison of the pressure change at the kerosene combustion in the combustor with the solid and discrete cavity has confirmed that modification of cavity causes change of distribution of the base pressure and the pressure along the channel length. The maximum pressure level in the combustion chamber with the discrete cavity was reached at the distance of about 150 mm from the fuel injectors. The maximum pressure level in the combustion chamber with the solid cavity is reached at $x = 235$ mm. Similar qualitative difference for two cavity types remained on the top wall.

The application of the discrete cavity causes significant growth of the base pressure. The base pressure in the combustion chamber with the discrete cavity rises fast by a factor of 3.5 – 4 and has a clear plateau during 20- 25 ms. The base pressure in the combustion chamber with the solid cavity is constant during the whole mode of the combustion chamber operation, and increases twice only at the end of the regime. The discrete cavity leads to the pressure growth at the kerosene combustion, not only in the base region, but also over the whole length of the combustion chamber. The relative growth of the static pressure in the combustion chamber compared to the corresponding pressure in the “cold” run (without fuel) was about 50% higher than in case of solid cavity. The solid cavity of the investigated geometry practically does not have effect on the ignition and combustion stabilization. This result may be conceivably explained by the fuel absence in the cavity and by the screening effect of air and fuel jets. Actually, the recirculation zone behind the cavity works as a flame stabilizer.

Investigation of fuel injection position was carried out. Fuel was injected into the shear layer into the base region (rim injection) and into the boundary layer before injector ramp. The tests of the model were carried out with two fuel supply systems. The main part of the fuel was injected through injector ramps as in the runs with the cavity, and in addition, the smaller part of the fuel (up to 10%) was injected along the normal direction to the stream in the isolator section before the injectors to provide in the boundary layer the fuel-air equivalence ratio close to one.

In the no-cavity tests with the simultaneous kerosene injection into the boundary layer and the combustion chamber, the kerosene ignition or combustion were not realized. The pressure distribution along the model channel differs weakly from the pressure distribution in the no-fuel run. Kerosene ignition and combustion did not realize either in the run without fuel injection into boundary layer before the injectors. Installation of the cavity resulted in the intensive combustion over all the combustor at **P**=0.95bars and $\mathbf{T_t}$=2470K.The similar results were obtained at Mach number 3 and 3.5.

The maximum level of pressure and heat fluxes on the top and bottom walls in the runs without cavity approximately corresponds to the run with the solid cavity. But the position of the pressure maximum is displaced upstream, and the typical pressure “gap” is situated behind the base backward facing step, i.e. in the cross section corresponding to the cross section behind the cavity. The start of the pressure rise is displaced upstream for 30 – 40mm, i.e. roughly for the cavity width. The experiments performed have demonstrated that in the no-cavity runs the kerosene supply in the boundary layer before the injector wedges does not guarantee effective ignition of hot kerosene.

The investigations of propane-fueled combustion chamber were carried out at Mach number 3 and 3.5 in the run with the above-mentioned flow parameters at the hot kerosene combustion. As a result, it was found that intensive combustion of propane at Mach number 3.5 did not realize under these conditions. Therefore the following runs with propane at Mach number 3.5 were performed, with the flow parameters at the combustor entry, which were increased up to the maximally achievable ones in a hot-shot wind tunnel (2.5 bars, 3000K). However, even at these parameters did not realize the intensive combustion of propane over the all combustor.

In this context the possibility of propane ignition at Mach number **M**=3 was checked to determine the ignition and combustion conditions. Due to the absence of the propane combustion at Mach number of 3.5, the runs were performed at high parameters: **P**=0.95 bars, $\mathbf{T_t}$=3000 K. The fast pressure growth up to maximum value in the base region and in the over all channel was. The intensive propane combustion under these conditions was taking place up to 60ms. The decrease of the full temperature up to 2700 K with the same static pressure at the combustion chamber entrance showed that there was only short local ignition and combustion of propane.

The heat fluxes in the runs with propane were in agreement with the static pressure change in the model channel. Results obtained indicate the high combustion efficiency during propane combustion. At the intensive combustion of propane, the value and character of changing the combustion efficiency differed from the runs with kerosene combustion. Combustion efficiency increased along the channel and reached the maximum value near the exit of the combustor.

The check of the propane ignition at Mach number **M**=4 with the maximum parameters ($\mathbf{T_t}$=3000 K, **P**=2.2 bar) has demonstrated that even under these conditions the brief (not more 10 ms) local ignition of propane took place in the divergent part of the combustion chamber. Probably it is related to the stabilizing effect of a Pitot pressure rake at the combustion chamber exit.

The analysis of experimental data obtained at the combustion of hydrocarbon fuels has been performed for understanding of the combustor operation and creating the scheme of ignition process and flame propagation over all the combustor. Results of processing and analysis were comparing with the data of the previous researches of combustion of hydrogen. These results allow defining the flow structure and combustion efficiency depending on geometry and type of flameholder and geometry of the combustor, airflow parameters at combustor entry, fuel type, and total and local fuel/air equivalence ratio.

The results obtained allowed to ascertain that in contrast to all previously well-known data, the fuel ignition in the present tests was realized not in the recirculation region behind the backward step, but in the vicinity of the shock wave/boundary layer interaction regions on the combustion-chamber walls or behind these regions, nearby the combustion chamber corner point. Initially, the fuel self-ignition occurred in the near-wall region of the flow. After that, the flame can propagate upstream and/or downstream through the boundary layer. After the fuel self-ignition in the recirculation region behind the backward-facing step or behind the rear wall of the cavity, considerable rise of static pressure in the entire volume of combustion chamber occurred. This conclusion is confirmed by visualization of OH-radicals radiation in the channel

***Thus, the performed investigations allow concluding*** that application of the discrete cavity allows speeding up the “kindling” of the combustor. It is accompanied by the significant, more than 50%, growth of the pressure over the whole length of the combustion chamber, including the base pressure.

The solid cavity of the studied geometry has no virtual effect on the ignition and combustion stabilization. This result may be conceivably explained by the fuel absence in the cavity and by the screening effect of air and fuel jets.

The studies performed have shown that fuel injection organized before the step (before the injectors) can be an effective means of the ignition control. In this case, it is required to optimize the position of the initial fuel injection in the longitudinal and transverse directions in order to improve mixing and provide for the required level of air/fuel equivalence ratio in the recirculation region or in the mixing layer. Very probably, the absence of well-prepared mixture in the recirculation region under high flow velocities conditions at the combustion chamber entrance presents a main obstacle for self-ignition.