History of scramjet propulsion development

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Abstract. In the paper a historical overview of scramjet propulsion development is presented. Three main stages of development of hypersonic summer programs are distinguish. The conclusion about the importance of the development of three-dimensional computer models describing the process in the scramjet is made.

1. Introduction
This historical review will primarily be useful to engineers, who are engaged in the development and implementation of promising hypersonic technologies. This paper describes the path that the programs on the creation of scramjet for the last 60 years have passed. Hypersonic ramjet air-jet engines (scramjet) have a basic scheme of operation is much simpler than other types of aircraft engines.

However, the practical implementation of the scramjet is very complex due to a number of principal reasons. To overcome these problems will have to spend a considerable amount of time. One of the basic problems of creating a scramjet is the organization of combustion of fuel in combustion chambers, organization of effective ignition of fuel components and the instability of the processes of ignition and combustion with respect to various gasdynamic perturbations. An important problem in the operation of the ramjet is the maintenance of the thermal regime of its design throughout the time of operation.

In this paper, it is proposed to consider how the development of experimental and computer technology influenced the trends in the development of hypersonic technologies. For this purpose, a well-known book by W. Heiser and D. Pratt [1], the book of E. Kuran and S. Marti [2] and the book of S. Segal [3] were used. The article [4], devoted to the history of the development of supersonic and hypersonic topics in the laboratory of the US Navy, was also used [4]. It should also be noted the work of Sabelnikov and Penzin [5,6], which provides an overview of the research on the development of a scramjet in Russia.

2. Advantages and disadvantages of ramjet and scramjet
The efficiency of jet engines is usually estimated by the specific impulse - the ratio of thrust to the second fuel consumption. This indicator is also a measure of the efficiency of the engine. The specific impulse of various engines is shown in figure 1.
It follows from the diagram that according to the specific impulse rocket engines are much inferior to air-jet engines of all types. This is due to the fact that the oxidant is also included in the fuel consumption of the rocket engine, which the air-jet engine takes from the atmosphere. In connection with this, possible applications of ramjet and scramjet are the creation of hypersonic aircraft (cruisers), which will make it possible to make large flights quickly enough. (from Moscow to Tokyo for 2-3 hours) at a speed of 4÷8 M, as well as the creation of reusable accelerators for launching missiles into space, which will reduce the cost of bringing cargo into space.

**Figure 1.** The specific impulse of various engines (https://en.wikipedia.org/wiki/Scramjet).

However, the ramjet and scramjet have several limitations. First, the drag of ramjet and scramjet should be more than that of a rocket due to the fact that it is necessary to take air from the atmosphere. This leads to more heating of the ramjet and scramjet than for rocket engines. In connection with this, the problem of creating heat-resistant strong materials is especially acute.

Secondly, high flight speeds lead to the fact that the characteristic time of the gas passage through the combustion chamber is very small (1 ms) and comparable to the time of self-ignition. In connection with this, burning of fuel can take place in the nozzle. Therefore, it is necessary to use tricks (caverns, throttle valves, pylons, etc.) for efficient mixing of fuel and air. It should also be noted that the combustion in the duct can sometimes cause choking. Therefore, the following restrictions exist. First, the scramjet can not operate at a speed of less than 4 M (another engine is needed to accelerate to the operating interval). Secondly, it is necessary to correctly integrate the engine and the "bird" to implement flight mode in a wide range of Mach numbers. In this paper, three stages of development of the ramjet are highlighted. Below you will find detailed information about each stage.

3. **The first stage. Podded engine**

At the first stage of the creation of the scramjet, an external accelerator was investigated. At this stage, the engine was created separately from the aircraft. Several experimental installations were created, operating according to the scheme of the connected air duct. The best example of such
engines is NASA HRE (Hypersonic Research Engine) [1] (figure 2), as well as the Russian device created by the group E.S. Shchetinkov in NII-1 [2] (figure 3). These engines use a large axisymmetric ledge for external compression. And the appearance of the engine is very similar to a gas turbine. As a fuel that cooled the walls of the combustion chamber in NASA HRE hydrogen was used. Russian engine uses kerosene.

Figure 2. Appearance of NASA HRE [7].

Figure 3. The appearance of the first Russian scramjet tested at NII–1 in 1964 by Kulibyakin and Penzin [6].

In 1954, it was decided to create an experimental rocket-propelled aircraft equipped with rocket engines. After the X-15 plane crash, the aircraft was damaged, but it was decided to use the restored X-15A-2, with the podded NASA HRE engine [3]. The main purpose of the research was to create a jet engine, which will achieve a speed of 3 to 8 Mach, and uses hydrogen as a fuel. In 1968, it was decided to close the NASA HRE program. By that time, two axisymmetric models of different geometry were created. To cool the walls of one model, hydrogen was used, which takes heat from the
wall, heats up and is more easily ignited. To cool the walls of another model located on the experimental platform, water was used. Measurements of heat fluxes were made. Strength properties of the structure were calculated in such a way as to withstand more than 50 cycles of starting the propulsion system.

Unfortunately, in the last flight of the X-15A-2 due to the high flight speed of 6.7 M, the outer shell of the aircraft was heated to 1480 °C. That led to the burning of the airplane shell and the appearance of holes in the metal parts (figure 4). Despite such damage, the plane landed successfully, but never flew again. A huge number of scientific results were obtained as a result of ground tests of this engine. As a result, it was found that the thrust of this type of engine does not exceed the external drag of the aircraft. Therefore, it was decided that it is necessary to integrate the engine into the aircraft.

4. The second stage. 2D engine integrated in aircraft
In the second generation of scramjets, the engines of fairly simple geometries (2D) were investigated, which were integrated into the aircraft. It should be especially noted that in these types of aircraft the engine itself is located after the front of the head shock wave. This means that the necessary compression for the engine is created by the aircraft itself. Also in this configuration, the engine drag is much less than the drag of hypersonic aircraft. One example of such integration is the spacecraft NASP (National Aero-Space Plane) [4], which was created by the USA in 1985-1994. The main idea of NASP was to create a hypersonic aircraft of a new generation with a horizontal launch and landing, developed by the United States to create a reliable and simple means of mass lifting people and cargo into space. The expected form of the device is shown in figure 5. For this purpose, it was planned to create a power plant, which would consist of a gas turbine engine, a ramjet engine, and a rocket engine. The program proved to be very expensive and technologically unfeasible. Despite the fact that because of this program was canceled, the results obtained in basic research, found application in
subsequent programs (Hyper–X). For example, the Jachimowski kinetic schemes [10] for describing the combustion of hydrogen fuel in air are used today.

![Figure 5. Prospective view of the apparatus a NASP (drawing (left) and photo (right) taken from the site https://ntrs.nasa.gov/).](image)

In the new NASA program "Hyper–X" [11], which is a continuation of the NASP program, it was decided to abandon the creation of a spacecraft. Instead, it was proposed to create a small hypersonic aircraft with hydrogen-fueled scramjet. NASA's Hyper–X program was designed to conduct flight tests of the unmanned experimental hypersonic X–43A. Appearance of the device is shown in figure 6.

![Figure 6. Appearance of the X-43A (drawing).](image)

To accelerate (output to the required speed and altitude), the upper stage of the Pegasus rocket was used. The first version of the X–43A was designed to achieve a speed above the Mach number of 7 - about 8000 km/h (2.24 km/s) at an altitude of 30000 m or more. It was developed as a single-use system. Only three models have been built. The first flight - June 2001 (failure, destroyed 11 seconds after the release by command of a security officer, fell in the Pacific) because of a control system error. The other two successfully completed the program - a ram jet engine worked for 10 seconds,
followed by a 10-minute glider drop. Both models were drowned in the Pacific Ocean. The second flight X–43A - March 27, 2004, was in normal mode. The third flight set a speed record at 11.850 km/h (Mach 9.6 = 3.2 km/s) on November 16, 2004.

In addition to the X–43A, the X–43B, X–43C, X–43D are developed in the Hyper-X program. The appearance of the X–43B is shown in figure 7. In this hypersonic aircraft, it is planned to use the ISTAR engine (Integrated Systems Test of an Air-Breathing Rocket) [5]. ISTAR uses a liquid-rocket hydrocarbon engine for initial acceleration, a ramjet engine at speeds higher than 2.5 M, and a scramjet at speeds higher than 5 M. The device must reach speeds above 7 M. When an X–43B exits into space, a rocket engine is again launched.

![Figure 7. Appearance of the X-43B (drawing).](image)

The X–43C is an X–43A version in which the scramjet engine on hydrocarbon fuel HyTECH [6] (figure 8). While most ramjet projects use hydrogen fuel today, HyTech operates on conventional kerosene-type hydrocarbon fuels. Currently, a full-scale engine is being built.

In 2002, HyShot hypersonic aircraft was successfully launched [14,15], and demonstrated successful combustion in the combustion chamber at a speed of 7.8 M and in the altitude range from 36 km to 25 km. At the first stage of the experiment, the apparatus was lifted by the Terrier-Orion Mk70 to a height of 300 km and dropped from this height. As soon as the device reaches the speed of 7.5 M, the process of measuring the operation of the scramjet starts. After that, the engine lasted 6 seconds [14]. The apparatus consisted of a wedge, and two rectangular scramjet chambers arranged symmetrically relative to the plane of symmetry of the apparatus. During the flight one of the engines worked, while the injection of fuel into the second was not carried out. Appearance of HyShot–2 is shown in figure 9.

![Figure 9. Appearance of HyShot-2.](image)

From 2009 to 2012, flight tests were carried out under the HIFiRE program [16,17]. As in the case of the HyShot experiment [14,15], in the first stage of the flight the apparatus is lifted with a Terrier-Orion Mk70 missile and dropped. The appearance of the HIFiRE-2 is shown in figure 10. The apparatus consisted of an air inlet (two wedges) and scramjet chamber with two cavities arranged symmetrically relative to the symmetry plane of the apparatus. As a fuel, a surrogate mixture of ethylene, methane and heptane was used. The engine is dual-mode, therefore both the ramjet mode and the scramjet are implemented. In the experiment, the pressure distribution on the chamber wall and the
Mach number were measured. Before the flight, ground tests were conducted on the HIFiRE Direct-Connect Rig (HDCR) experimental setup located at NASA Langley [7].

**Figure 8.** Appearance of the scramjet engine on hydrocarbon fuel HyTECH (https://www.globalsecurity.org/military/systems/munitions/hytech.htm).

**Figure 9.** Appearance of HyShot–2 [14].
It should be noted about Russian works on this topic. In CIAM, the development of the hypersonic aircraft "Kholod" was carried out [9,10]. The hypersonic flying machine "Kholod" (figure 11) was created on the basis of the SA–5 surface-to-air missile 5B28, developed at Khimki KB "Fakel" under the direction of the general designer P.D. Grushin [2]. The choice of this missile was due to the fact that the parameters of its flight trajectory were close to those required for flight tests of the scramjet. It was also considered important that this missile was removed from armament, and its cost was low.

The combat part of the missile was replaced by the head compartments of the hypersonic aircraft "Kholod", which housed the flight control system, a container for liquid hydrogen with a displacement system, a system for regulating the flow of hydrogen with measuring devices, and, finally, an experimental scramjet E–57 of an axisymmetric configuration. By 1999, a total of seven flights were conducted. The first two flights with overall-weight mock-ups of the head compartments according to the flight design test program made it possible to debug a new missile control system to provide the required trajectory. In five flights, a real ramjet was used with detailed preparation of the combustion chamber's flow path. In three flights, liquid hydrogen was fed into the combustion chamber of the scramjet. The scramjet time operation in flight increased from one test to another and in the latter was 77 seconds, corresponding to the maximum flight time of the S–200 missile. The maximum achieved speed of the flight "Kholod" was 1855 m/s, which corresponds to the Mach number M = 6.49. It was established that the combustion chamber was still operable after it was turned off.

Another of the well-known hypersonic projects is the Hypersonics Flight Demonstration program (HyFly). The hypersonic aircraft is launched from an F–15E aircraft and accelerated to operating speed using a solid-propellant rocket booster. The HyFly engine is a dual-mode Dual-Combustion Ramjet (DCR). In this engine, two different air intake systems are implemented, which allow the engine to work either as ramjet or scramjet. In addition, the engine operates on a conventional liquid hydrocarbon fuel (JP–10), which is much easier to operate than liquid hydrogen. The DCR concept was developed by the Applied Physics Laboratory (APL) of Johns Hopkins University and in May
2002. APL successfully tested the HyFly engine in a wind tunnel at a speed of 6.5 M. The photograph of the experiment is shown in figure 12.

![Figure 12. Appearance of HyFly. Photo of the Johns Hopkins University.](image)

Another of the experiments that gave hope for the soonest implementation of the scramjet was X–51 [21]. The X–51A was launched from Edwards Air Force Base in California. The device was raised to a height of 50 000 feet under the left wing of the B–52 Stratofortress airborne test center, as shown in figure 13. Then the missile accelerated the X–51A to a speed of 4.8 M.

![Figure 13. Hypersonic aircraft X-51 before launch from the aircraft B-52.](image)

Once the X–51A disconnected from the accelerating rocket engine, its own engine SJY61, which is shown in figure 14, has started. In the first seconds of operation, a mixture of ethylene and jet fuel JP–7, and then exclusively jet fuel JP–7, was used as fuel. As a result, the device reached an altitude of about 70 000 feet and a maximum speed of 5 M.
5. The third stage. 3D engine integrated in aircraft
In connection with the development of new computer methods in the 90's, it became possible to explore different types of 3D virtual models of scramjets. Therefore, in the third generation of ramjets, engines with complex three-dimensional geometry are used. This decision was made due to the fact that the second generation of ramjets had limitations. These include the strength of the entire structure; as well as insufficient system efficiency. Three-dimensional scramjets include engines with rounded or elliptical forms. The main advantages of elliptical motors are that for the same mass flow, a smaller surface area of the chamber is required, which leads to a reduction in drag and cooling requirements. The design weight also decreases due to the inherent strength of the rounded structures.

An example of such a ramjet with complex geometry is a rectangular channel that goes into an elliptical (Rectangular-to-Elliptical Shape Transition - REST) [22–25]. This configuration was investigated by NASA Langley in 1997 [22]. This scramjet consists of a rectangular inlet, which allows it to effectively integrate it into the engine and elliptical engine. A photograph of this engine is shown in figure 15.

![Figure 15. Photo of NASA Langley REST [22].](image-url)
There are various types of integration of this type of engine in a hypersonic aircraft. Figure 16 shows the proposed integration scheme of NASA's Langley REST engine, proposed in [22]. In this scheme, it is planned to place several engines on the lower surface of the apparatus. In the HIFiRE 7 project [24, 26], the REST engines are located as shown in figure 17.

Figure 16. The proposed integration scheme of NASA Langley REST engine [22].

Figure 17. Scheme HIFiRE 7 REST [24,26].

The REST ideas are also implemented in the hypersonic aircraft LAPCAT–MR2 [27] (HEXAFLY–INT - High-Speed Experimental Fly Vehicles - International). In this hypersonic aircraft, the engine is integrated into the aircraft, as shown in figure 18.

Another example of using the three-dimensional geometry is scramjet Hypersonic Collaborative Australia / United States Experiment (HyCAUSE) [28]. The appearance of this hypersonic aircraft is shown in figure 19. As a result of wind tunnel experiments at the University of Queensland, this engine shape was found to be optimal and was used in further flight tests [28].

6. Conclusion
This paper presents a historical overview of the three stages of development of the ramjet. In the third generation of ramjets, engines with complex three-dimensional geometry are used. Therefore, in addition to creating quasi-one-dimensional and two-dimensional computer codes designed for modeling processes in ramjet [29 –35], it is especially important to develop three-dimensional codes.
Figure 18. Appearance of the hypersonic aircraft LAPCAT-MR2 [27].

Figure 19. Appearance of the hypersonic aircraft HyCAUSE [28].

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