Analysis of development trends of power-units for high-speed flying vehicles

K Yu Arefyev$^{1,2,3}$, N V Kukshinov$^{1,2}$ and A N Prokhorov$^{1,3}$

1 Central Institute of Aviation Motors, Aviamotornaya Street 2, Moscow 111116, Russia
2 Bauman Moscow State Technical University, 2nd Baumanstaya Street 5, Moscow 105005, Russia
3 Moscow Institute of Physics and Technology, Institutskiy Pereulok 9, Dolgoprudny, Moscow Region 141700, Russia
E-mail: prokhorov@ciam.ru

Abstract. The review of modern achievements in the field of development of high-speed flying vehicles with a power plant is presented, based on the information available in open sources. Modern development projects for such vehicles are considered. The main focus is on the projects dedicated to scramjets development and started to carrying out in the last decade. The ways of solving the problems connected with the development of high-speed aircraft with power plants based on scramjets are analyzed. The materials presented in the paper can be useful at the stages of setting tasks and implementing various projects for the development of civil high-speed vehicles.

1. Introduction
Development of high-speed aircrafts capable of making a long active flight in the atmosphere at speeds corresponding to the Mach numbers $M > 5$, is one of the actual problems in the field of aerospace engineering, designed for high-speed transport aviation and space exploration. The solution to this problem is impossible without the development of engines that have several times better efficiency than rocket engines. It is estimated that scramjets for hypersonic flight speeds seem to be the most economical for power plants of high-speed flying vehicles of various classes.

The period of global aerospace systems projects such as the National Aero-Space Plane (USA) [1], the Japanese Aero-Space Plane (Japan) [2], Hyperplane (India) [3], the Chinese Aero-Space Plane (China) [4], Zanger (Germany) [5], STS-2000 (France) [6], Tu-2000, MAKS [7] (Russia) ended when it became obvious that the key element of the considered aircrafts was the power plant, which had not been adequately developed. This, in turn, led to new fundamental and applied research of demonstrators of high-speed ramjets integrated with experimental flying vehicle. The goal of most of the works was the choice of technical appearance, as well as confirmation of its efficiency and robustness at hypersonic flight speeds ($M > 5$).

The greatest progress in the field of autonomous (after separation from the accelerator) flight tests of demonstrators of power plants on the basis of the scramjet in integration with experimental flying vehicle is observed in the USA. To date, flight tests have been conducted in the USA for demonstrators of scramjets in integration with experimental flying vehicles X-43A [8], the Hypersonic Flight Demonstration Program (HyFly) [9], the Free Flight Vehicle [10],
X-51A [11]. Similar projects of integrated hypersonic demonstrators for autonomous flight testing of high-speed jet engines are being developed in Russia [12,13], France (LEA) [14], India (HSTDV—Hypersonic Technology Demonstrator Vehicle) [15], China [16] and other countries, but have not yet been brought to flight tests.

In this paper, known programs for development of high-speed aircraft demonstrators with power plants are reviewed and analyzed. The main trends in the development of power plants for high-speed aircraft demonstrators are reflected. The problems of scramjet development and ways to solve these problems are analyzed.

2. Review of achievements in field of development of high-speed aircrafts with power plant

Research in the field of development of high-speed aircrafts with power plants based on scramjets is conducted in many countries (Russia, USA, France, Germany, Japan, China, India, etc). The beginning of research is considered to be the invention of a scramjet in 1957 by Professor Shchetinkov in Russia [17]. Regardless of Shchetinkov, in the USA, Ferry also put forward the idea of a scramjet with combustion in a supersonic flow [18]. It should be noted that the first foreign publications on the theory of scramjets in the USA and France date back to 1958 [19,20].

In the USA, the first scramjet for flight tests in order to demonstrate the thrust and economic characteristics in real flight conditions was created under the Hypersonic Research Engine (HRE) program, which was opened in 1964 [21]. This engine had an axisymmetric configuration: an air intake with a profiled central body, an annular combustion chamber, an axisymmetric nozzle. Liquid hydrogen was used as a fuel. Flight tests of this engine were planned to be carried out on the X-15 rocketplane with flight Mach number \( M = 6 \). Due to the failure of the supply of liquid hydrogen to the HRE combustion chamber in the first flight and the crash of the X-15 aircraft in the second flight, the HRE flight test program was closed. However, a structural assembly model (SAM) and an aerothermodynamic integration model (AIM) of the HRE have undergone a large cycle of bench tests.

In Russia in 1964, Kolyubakin and Penzin were first who tested a large-scale axisymmetric model of high-speed ramjet (prototype of the flight model) in a free flow with a Mach number \( M = 6 \) [17]. In France, the study of the concept of an axisymmetric ramjet was carried out under the ESOPE program from 1966 to 1972 [22].

For the first time in the world, flight tests of the demonstrator of an axisymmetric high-speed hydrogen-fueled ramjet were carried out in Russia in 1991 with the help of the hypersonic flying laboratory Kholod, which was developed on the basis of the SA-5 missile [23, 24] (figure 1). Then in the period from 1992 to 1998, together with France, and then the USA, four more flight tests of an axisymmetric high-speed ramjet demonstrator were carried out [25–27]. In these flight tests, the demonstrator engine was not separated from the booster. The possibility of realizing an efficient working process in a combustion chamber at supersonic flow velocities at the entrance in conditions of a real hypersonic flight was practically investigated. Subsequently, the methodology for conducting such flight tests was implemented by Australian scientists [28] to study the working process in model combustion chambers of high-speed ramjets.

To date, as a result of the large amount of computational and experimental studies of the thrust characteristics of axisymmetric scramjets, quite high values of the specific impulse determined by internal parameters, have been obtained. But in terms of its intended purpose, the thrust of the engine should exceed the external drag of the complex system “flying vehicle and engine”, which subsequently led specialists to consider scramjets integrated with vehicle [29] in an autonomous flight.

Russian projects of integrated hypersonic demonstrators for carrying out autonomous flight tests of scramjets IGLA and GLL-AP are known [13] (figure 2). Investigations of the characteristics of the intake of the module GLL-AP were carried out in the CIAM. In the same
Figure 1. Hydrogen axisymmetric high-speed ramjet demonstrator Kholod (a) before bench tests (b) before flight tests.

Figure 2. Integrated hypersonic demonstrators for flight tests (a) supposed flight of GLL-VK (b) GLL-AP model.

study, the integration of the intakes with the nose of the fuselage of the aircraft was carried out on small models. The aerodynamic models of GLL-AP were studied at “small” hypersonic Mach numbers on the wind tunnels of ITAM SB RAS (Institute of Theoretical and Applied Mechanics of Siberian Bureau of Russian Academy of Science). The aerodynamic model of the “IGLA” under “medium” and “large” hypersonic Mach numbers was tested both in TsNIIMASh [30] and ITAM SB RAS. Tests of the combustion chamber of the engine-demonstrator GLL-AP on the connected air duct were carried out at the C-16VK CIAM facility. The combustion chamber under investigation had a regenerative cooling system.

Also on the C-16VK facility tests of integrated models “aircraft and engine” were conducted. For the X-2000 facility model, at the “small” hypersonic Mach numbers, a positive effective thrust generated by the model engine in integration with the experimental aircraft was obtained. During the test, the longitudinal force detection sensors first showed the drag of the experimental object. After the fuel supply and realization of the combustion process, the excess of the force generated by the demonstrator engine in integration with the experimental aircraft over the drag of the experimental object was recorded. In the tests gaseous hydrogen and natural gas were used as fuel. The presented experimental data convincingly confirm the thrust efficiency of scramjet integrated with an aircraft on the “small” hypersonic Mach numbers.

Modern projects of civil hypersonic aircraft development are of great interest. From an economic point of view, a hypersonic civil aircraft with flight numbers Mach M = 5–8 takes precedence over supersonic passenger aircraft like Tu-144 and Concord in that it can make a direct and reverse transcontinental flight within one day. At this stage, numerical and experimental studies are carried out on the efficiency of the working process in the internal
flow path, aerodynamics of the aircraft, questions of the efficiency of the intake are covered, and the characteristics of the heat-resistant materials are studied. Thus, within the framework of the SHEFEX (Sharp Edged Flight Experiment), and SHEFEX-II [31–33] projects flight tests were conducted, the purpose of which was to determine the characteristics of modern composite materials as components of heat protection. The tests were carried out in a corridor of altitudes of 20–90 km at speeds corresponding to Mach numbers M = 7–11.

In the European Union, the main program in the field of civil hypersonic technologies was the LAPCAT (Long-Term Advanced Propulsion Concepts and Technologies) program [34,35] to develop an airplane with flight speeds corresponding to Mach number M = 5–8, continuation of which are the completed HEXAFLY (High-Speed Experimental Fly Vehicles) project [36] and the ongoing HEXAFLY-INT (High-Speed Experimental Fly Vehicles—International) [37–41]. Within the framework of these projects, complex studies of aircraft with a scramjet on hydrogen fuel are conducted. The model itself (figure 3) differs from the known developments of the “waverider” type by the dorsal intake and the two-way fuel delivery system. The power plant is a supersonic combustion chamber of an elliptical cross section, passing into a nozzle, expanding first in one plane, then in two. Based on this configuration, a test module was created in CIAM (figure 4), the tests of which were carried out with simulation of high-altitude flight conditions with the Mach number of the oncoming stream M = 7.5. In the experiments, a positive aero-propulsive balance was obtained (the thrust generated by the module exceeded the total aerodynamic drag) at a level of the oxidizer excess factor = 0.6. However, before the flight tests of the aircraft of the presented configuration, flight tests of the glider without a power plant will be carried out for testing the output of the aircraft for a given trajectory and undocking from the booster.

Another promising project of the hypersonic aircraft is the SKYLON project [42], the scheme of which is shown in figure 5. This project is an evolutionary continuation of HOTOL (Horizontal Take-Off and Landing) and X-33 programs. The length of the aircraft is more than 80 m, the maximum weight is about 275 t. The aircraft will be able to bring to the low equatorial orbit...
Figure 4. Facility module HEXAFLY-INT.

about 12 t of payload. The combined power plant (figure 6) consists of an intake circuit, a heat exchanger for cooling air before entering the compressor, air-breathing engine and liquid rocket engine. This aircraft is designed for a flight with Mach number $M = 16$, while the air-breathing engine operates up to the Mach number $M = 5.5$. The possibility of using the classical air-breathing engine scheme are caused by the presence of heat exchanger. Two engines are on the ends of the wings of the aircraft and have an axisymmetric intakes.

A similar concept of the use of air-breathing engine with pre-cooling of air after the intake for flight with speeds corresponding to the Mach number $M = 5$ is used in the JAXA (Japan Aerospace Exploration Agency) project [43,44]. The main difference from the SKYLON project is that the JAXA project provides for a flat intake with a central location, and the air-breathing engine itself is located inside the flat flow path (figure 7). The design of the engine provides variable geometry of the intake and nozzle.

Relatively recently the scramjet development began in Brazil. The Department of Aerospace Science and Technology (DCTA) presented the 14-X project [45] (figure 8). Within the framework of this project hydrogen scramjet integrated with the aircraft, is being developed. In the flight experiment, it is planned to accelerate aircraft with a two-stage accelerator consisting of S30 and S31 missiles, up to the Mach number $M = 6$ at an altitude of 30 km. The planned duration of the scramjet operation is 4 s. The proposed subsequent flight tests must be carried out with the achievement of the Mach flight $M = 10$.

In addition to hypersonic civil aircraft projects combined power plants with scramjet circuit are considered for use as part of reusable aircrafts for bringing payloads into orbit (figure 9). So in work [46] a Rocket-Based Combined Cycle propulsion system with two circuits and 4 operating
Figure 5. Skylon aircraft scheme.

Figure 6. Multi-mode SABRE.

modes is proposed. In the first mode, the air-breathing engine circuit operates, accelerating the aircraft to the flight Mach number flight \( M = 3 \), then the second circuit is turned on and
the engine operates as a ramjet and accelerates the aircraft from $M = 4$ to $5–6$, then, due to geometrical changes in the flow path, in the scramjet mode the aircraft accelerates to the flight Mach number $M = 8$, and finally, the last mode is the operation of a scramjet circuit as a rocket engine nozzle and acceleration to $M = 10$.

Also in the world there is a large number of fundamental scientific studies that are not linked to specific aircrafts and aimed at collecting data on the physics of processes occurring in hypersonic flow around bodies and hydrogen burning in a supersonic stream under flight and stand conditions. Such works include the completed work of HyCAUSE, HyFly, HyShot, Scramspace [47–50].

Programs for the development of hypersonic aircraft in the United States are aimed primarily at creating a cruise missile that has a scramjet with Mach number $M = 5–6$. Hyper-X program is
especially worth mentioning, within the framework of which successful flight tests of hypersonic aircraft X-43A were carried out [51].

X-43A flight tests [52], scheme of the flying vehicle is shown in figure 10, were successfully held in 2004. In two launches, during the first of which Mach’s flight number was $M = 6.8$, during the second $M = 9.6$, the claimed engine thrust was demonstrated. Hydrogen was used as fuel; however, combustion was initiated with the help of silane, which indicates problems with self-ignition of fuel in this engine. The power plant when flying at a speed corresponding to the Mach number $M = 10$ did not work more than 10 s, so it can be argued that the cooling system and the resource work of the scramjet were not considered in this work, and the aim was to demonstrate the possibility of the engine work at such flight speeds.

From the point of view of the work of the resource scramjet, the most interesting for analysis is the program X-51A [11], within which the power plant operating on hydrocarbon fuel namely on aviation kerosene JP7, was developed. Although cryogenic hydrogen has many advantages with respect to kerosene (greater cooling capacity, better thermal stability, potentially higher specific impulse), the use of hydrocarbon fuels allows storage and transportation using ready-made infrastructure. Also the advantage of hydrocarbon fuel with respect to hydrogen is the large volume calorific value.

Hydrocarbon fuels (in particular, kerosene) belong to the endothermic fuels. Such fuels are characterized by an increase in cooling capacity due to heat absorption during endothermic reactions that occur when the fuel is heated in a regenerative cooling system. Reactions begin to occur at sufficiently high fuel temperatures ($750$ K according to data [53, 54]), which are characteristic for cooling systems of combustion chambers of scramjets. The temperature in the combustion chamber can reach the temperatures that occur in the liquid rocket engine, but due to the significantly lower fuel mass-flow rates, the coolant is heated more and the fuel in the cooling system enters the endothermic reaction zone, which leads to an increase in the cooling capacity.

In the regenerative cooling systems of scramjets combustion chambers on hydrocarbon fuels, one of the main problems is the instability of the flow of fuel [55, 56]. Also undesirable is film
boiling, which leads to a decrease in the heat transfer coefficient and, as a consequence, burnout of the wall. Another factor that must be taken into account is the peaks of heat fluxes caused by the shocks hitting on the walls.

In the project X-51A, the development of a hypersonic flying vehicle which could reach a speed corresponding to the Mach number \( M = 7–8 \), have a corridor of heights of 10–30 km, a flight range of 1300 km and a run time of at least 12 min was planned. The layout of X-51A is shown in figure 11, the device had a mass of 1.815 kg with a march stage length of 4.27 m. In addition to the large volume of bench tests, 4 flight experiments were conducted, the last of which took place in 2013, in which the power plant worked 210 s.

Recently, much attention has been paid in the United States to the development of hypersonic flying vehicle equipped with combined power units. Such vehicle can perform aircraft takeoff, landing, flight, and, if necessary, refueling in the air at subsonic speeds, as well as a long flight with supersonic and hypersonic speeds. According to the US, they have created a significant gap from potential competitors in the development of technologies for the creation of combined power plants. The project SR-72 (figure 12) is known, which is planned to be developed by 2030. It is assumed that SR-72 will be able to solve various tasks: defeat of time-critical targets, reconnaissance and surveillance of the territory of a potential enemy, and rapid withdrawal of spacecraft to near-earth orbit. The maximum design speed of SR-72 flight corresponds to the Mach number \( M = 5 \). According to the available information, a demonstrator of the technologies used in the SR-72 project, intended for FRV (Flight Research Vehicle) flight tests, is being created. The approximate date for the first flight tests of FRV is scheduled for the beginning of the 2020s.

The American-Australian International Hypersonic Flight Studies and Experiments Program (HIFiRE) is known [57–59]. The program is implemented jointly by the USA Air Force Research Laboratory (AFRL) and the Australian Defense Science and Technology Organization with the support of partners: Boeing (USA) and the University of Queensland (Australia).
Initially, the program provided for 9 flight experiments. They can be divided into 5 categories. The first category within the HIFiRE-0 phase is aimed at validating the flight control system, electrical systems, and software for subsequent flight testing. The second category (within the framework of the stages HIFiRE-1 and HIFiRE-5) is aimed at studying the boundary layer and other gas-dynamic phenomena. The experiments in the HIFiRE-2, HIFiRE-3 and HIFiRE-7 phases belong to the third category—the development of scramjet, and the experiments within the HIFiRE-4 and HIFiRE-6 phases belong to the fourth target category—flight control. Within the final stage of the HYFiRE-8, it is planned to consider the fuselage in integration with scramjet.

It should be noted that the numbering of projects does not correlate with the order of the experiments. The stages of the project contain a comprehensive set of scientific and technological works to ensure the achievement of hypersonic flight mode.
Table 1. HIFiRE experiments.

| Stage      | Description                                                                 |
|------------|-----------------------------------------------------------------------------|
| HIFiRE-0   | A simple experiment on the reorientation of aircraft                         |
| HIFiRE-1   | Test to change the structure of the boundary layer on a truncated cone       |
| HIFiRE-2   | Experiment on the operation of a dual-mode scramjet                          |
| HIFiRE-3   | Experiment on the evaluation of the formation of radicals in scramjet        |
| HIFiRE-4   | Experiment to control a glider re-entering the atmosphere                    |
| HIFiRE-5   | Change in the structure of the boundary layer on an elliptical cone          |
| HIFiRE-6   | Experiment on adaptive control of the glider with the scramjet               |
| HIFiRE-7   | Measurement of engine thrust with REST type intake                           |
| HIFiRE-8   | 30-second flight of aircraft with a REST-type scramjet                       |

The stages of the project are shown in table 1. The stages of the program that were completed by the flight experiment as of August 2017 are HIFiRE 0, 1, 2, 3, 4. The flight experiment on HIFiRE-6 was canceled.

An image of a REST type scramjet in which there is a transition from a rectangular section to an elliptical section is shown in figure 13. The concept of an aircraft with a REST-type scramjet approved for the last flight test of the HIFiRE program scheduled for October 2018 is shown in figure 14.

In recent years, interest in the development of detonation engines has increased in the world. In particular, in CNUDT (Chinese National University of Defense Technologies), a ramjet engine with a rotating detonation wave was developed and tested [6]. The engine tests were carried out in a free jet with the parameters of the incident flow corresponding to a flight with Mach number $M = 4.5$ at a height $M = 18.5$ km. Photos of the test object in the test bench are shown in figure 15.
As a result of the tests, the possibility of a stable rotating detonation wave with hydrogen and ethylene as fuel was experimentally demonstrated. Table 2 summarizes all reviewed projects.

In closing of the review of the development of high-speed-ramjet demonstrators, it is necessary to emphasize the urgency of the task of developing such demonstrators and the great experience accumulated in developed countries, thanks to the large amount of data obtained as a result of flight and ground-based experiments. However, it is also worth noting that the task of developing a resource demonstrator capable of carrying a large payload is unsolved today and requires additional research and improvement of calculation and experimental techniques.
Table 2. Projects summary.

| Name          | Mach number | Engine type       | Test type        | Year of end |
|---------------|-------------|-------------------|------------------|-------------|
| Kholod        | more than 6 | Scramjet          | Flight           | 1998        |
| IGLA          | 6-14        | Scramjet          | Free jet ground  | 2009        |
| X-2000        | more than 5 | Scramjet          | Free jet ground  | 2011        |
| SHEFEX        | 7-11        | No engine         | Flight           | 2011        |
| HEXAFLY-INT   | 7-8         | Scramjet          | Free jet ground  | Present     |
| SKYLON        | up to 16    | Combined          | Concept stage    | Present     |
| JAXA aircraft | up to 5     | Air-breathing engine | Free jet ground  | Present     |
| 14-X          | 6-10        | Scramjet          | Concept stage    | Present     |
| X-43A         | up to 9.5   | Scramjet          | Flight           | 2010        |
| X-51A         | up to 5.1   | Scramjet          | Flight           | 2011        |
| HIFiRE        | up to 7     | Scramjet          | Flight           | Present     |
| SR-72         | 5           | Combined          | Concept stage    | Present     |
| CNUDT engine  | 4.5         | Detonation ramjet | Free jet ground  | Present     |

3. Conclusions

Our deductions are as follows:

- The analysis of the works shows that an important task in the development of a hypersonic flying vehicles is the development of a ramjet for hypersonic flight speeds. The first works in the field of development such engines were published in 1957 by Professor Shchetinkov. A large volume of computational-theoretical and experimental research has allowed to implement several international programs with flying experiments (in Russia, the USA, Australia).

- The most important in development of ramjets for a hypersonic flight are the technologies for designing the flow path of the engine, the technologies of efficient fuel combustion and workflow control, the technologies for cooling high-temperature combustion chambers, the technologies for creating new engine and engine components based on high-temperature materials and coating and the technologies of flight and ground tests.

References

[1] Rausch V L and Morris C E K 1992 Technologies for the national aero-space plane (Int. Astronautical Congr. vol 92) (Int. Astronautical Federation) p 0869
[2] Maita M, Ohkami Y, Yamanaka T and Mori T 1990 Conceptual study of space plane powered by hypersonic airbreathing propulsion system 2nd Int. Aerospace Planes Conf. vol 1990 (AIAA) p 5225
[3] Gopalaswami R et al 1988 Concept definition and desine of a single-stage-to-orbit launch vehicle-hyperplane (Int. Astronautical Congr. vol 88) (Int. Astronautical Federation) p 0194
[4] Shusheng W and Kexun Zh 1990 Preliminary of the rocket-ramjet-rocket concept for HTO space plane (Int. Astronautical Congr. vol 90) (Int. Astronautical Federation) p 0264
[5] Krammer P and Schwab R R 1992 Engine technologies for future spaceplanes (Moscow Aero and Industry Engine vol 92)
[6] Poulguen M F, Doublier M and Scherrer D 1988 Combined engines for future launchers (AIAA/SAE/ASME/ASEE 24th Joint Propulsion Conf. vol 1988) (AIAA) p 2823
[7] Dmitriev V G 2005 The Problems of Development of Promising Aviation and Space Technology (Moscow: FIZMATLIT)
[8] McClinton Ch R 2006 X-43—scramjet power breaks the hypersonic barrier: Dryden lectureship in research for 2006 (44th AIAA Aerospace Sciences Meeting and Exhibit vol 2006) (AIAA) p 1
[9] 2007 HyFly overview Preprint (ONR-DARPA-Boeing-Aerojet)
[37] Ivankin M A, Nikolaev A A, Talyzin V A and Voloschenko O V 2015 Experimental investigations of the hydrogen combustion chamber for high-speed vehicle (20th AIAA Int. Space Planes and Hypersonic Systems and Technologies Conf. vol 2015) (AIAA) p 3617

[38] Pezzella G, Marini M, Reimann B and Steelet J 2015 Aerodynamic design analysis of the HEXAFLY-INT hypersonic glider (20th AIAA Int. Space Planes and Hypersonic Systems and Technologies Conf. vol 2015) (AIAA) p 3644

[39] Steelet J et al 2016 Numerical and experimental research on aerodynamics of high-speed passenger vehicle within the HEXAFLY-INT project (Proc. of 30th Congr. of the Int. Council of the Aeronautical Sciences vol 2016) (ICAS) p 0353

[40] Aleksandrov V Yu, Danilov M K, Gouskov O V, Gusev S V, Kuksinov N V, Prokhorov A N and Zakharov V S 2016 Numerical and experimental investigation of different intake configurations of HEXAFLY-INT facility module (Proc. of 30th Congr. of the Int. Council of the Aeronautical Sciences vol 2016) (ICAS) p 0380

[41] Aleksandrov V Yu, Kuksinov N V, Prokhorov A N and Rudinskiy A V 2017 Analysis of the integral characteristics of HEXAFLY-INT facility module (Proc. of the 21th Int. Space Planes and Hypersonic Systems and Technology Conf. vol 2017) (AIAA) p 2179

[42] Mehta U, Aftosmis M, Bowles J and Pandya S 2015 Skylyn airframe aerodynamics and SABRE plumes (Proc. of the 20th Int. Space Planes and Hypersonic Systems and Technology Conf. vol 2015) (AIAA) p 3605

[43] Taguchi H, Kobayashi H, Kojima T, Hongoh M, Masaki D and Nishida S 2015 Performance evaluation of hypersonic pre-cooled turbojet engine (Proc. of the 20th Int. Space Planes and Hypersonic Systems and Technology Conf. vol 2015) (AIAA) p 3593

[44] Taguchi H, Sato T, Kobayashi H, Kojima T, Olai K, Fujita K and Ohta T 2005 Design study on a small pre-cooled turbojet engine for flight experiments (13th AIAA Int. Space Planes and Hypersonic Systems and Technologies Conf. vol 2005) (AIAA) p 3419

[45] Martos J, Rego I and Toro P 2017 Experimental analysis of 14-X B hypersonic aerospace vehicle compression system (Proc. of the 21th Int. Space Planes and Hypersonic Systems and Technology Conf. vol 2017) (AIAA) p 2383

[46] Zhang H, Guo J, Xu Y, Du B, Wang Y and She W 2017 Research on TSRE reusable launch vehicle powered by turbo-aided RBCC engine (Proc. of the 21th Int. Space Planes and Hypersonic Systems and Technology Conf. vol 2017) (AIAA) p 2372

[47] Brown L, Boyce R and Tirtey S 2011 Numerical simulation of SCRAMSPACE I flight experiment (17th AIAA Int. Space Planes and Hypersonic Systems and Technologies Conf. vol 2011) (AIAA) p 2367

[48] Laurence S, Schramm J, Karl S and Hannemann K 2011 An experimental investigation of steady and unsteady combustion phenomena in the Hyshot II combustor (17th AIAA Int. Space Planes and Hypersonic Systems and Technologies Conf. vol 2011) (AIAA) p 2310

[49] Walker S, Rodgers F Paull A and Van Wie D 2008 HyCAUSE flight test program (15th AIAA Int. Space Planes and Hypersonic Systems and Technologies Conf. vol 2008) (AIAA) p 2580

[50] Dadd G, Owen R, Hodges J and Atkinson K 2006 Sustained hypersonic flight experiment (SHyFe) (14th AIAA Int. Space Planes and Hypersonic Systems and Technologies Conf. vol 2006) (AIAA) p 7926

[51] Marshall L, Corpening G and Sherrill R 2005 AIAA J. 2005 2332

[52] Baums C, Baumann E, Martin J, Bose D, Beck R and Stovers B 2005 AIAA J. 2005 3275

[53] Lader H and Nixon A 1971 J. Aircr. 8 200–7

[54] Sobel D and Spadaccini L 1997 J. Eng. Gas Turbines Power 119 334–51

[55] Hines W and Wolf H 1962 ARS J. 1962 361–6

[56] Hitch B and Karpuk M 1998 AIAA J. 98 3759

[57] Adamczak D, Alesi H and Frost M 2009 HIFiRE-1: Payload design, manufacture, ground test, and lessons learned (16th AIAA/DLR/DGLR Int. Space Planes and Hypersonic Systems and Technologies Conf. vol 2009) (AIAA) p 7294

[58] Smith T R, Bowcutt K G et al 2011 HIFiRE-4: A low-cost aerodynamics, stability, and control hypersonic flight experiment (17th AIAA Int. Space Planes and Hypersonic Systems and Technologies Conf. vol 2011) (AIAA) p 2275

[59] Bolender M, Staines J and Dolvin D 2012 HIFiRE-6: An adaptive flight control experiment (50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition vol 2012) (AIAA) p 252