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# Preface

Airbreathing hypersonic flight is a fascinating topic. Many attempts have been made to advance it in the direction of actual operation. Apart from military applications, which are not considered here, no study or project advanced far enough. Notable exceptions are the flights of the X-43A and the X-51A, which were pure experimental flight vehicles of rather small size.

The last two decades of the previous century have seen a number of studies of single-stage-to-orbit (SSTO) and two-stage-to-orbit (TSTO) space transportation systems. Airbreathing propulsion in form of ramjet and scramjet propulsion did play a deciding role. Another topic with much appeal was that of long-haul airbreathing hypersonic passenger flight, with flight distances ranging up to half around the globe. Such studies extended and continue into the present century. Of particular interest remained and still remains the propulsion technology. That regards the ramjet and in particular the scramjet, and also the detonation engine concept.

Basic research was and is conducted on propulsion technology and also concerning—after a, to some extent inexplicable neglect—the all deciding topic of laminar-turbulent transition of hypersonic boundary layers. The topic of real-elastic versus perfect-elastic airframe structure design technology, too, has not found the needed interest. It is of very large importance when considering the partly quite large airframes of potential hypersonic airbreathers and the necessary ground testing of their static and dynamic elastic properties, this all in view of the topic of airframe-propulsion integration.

Flight nowadays is considered to be hypersonic at flight Mach numbers above $M_\infty \approx 5$. The ramjet-propulsion domain today is seen in the interval $3 \lessapprox M_\infty \lessapprox 7$, followed by the scramjet-propulsion domain, which reaches up to $M_\infty \approx 12$. Because of the rising of dynamic pressure with $M_\infty$, both flight domains imply flight at altitudes much higher than those of the turbojet domain. Thermal loads on the flight vehicle—depending strongly on the state of the boundary layer, either laminar or turbulent—are rising extremely with rising flight Mach number. Hence knowledge of the location, the shape and the extent of the laminar-turbulent transition zone is of utmost importance. However, this is a problem, which still is not mastered to the necessary degree.

The thermal loads topic via structural aerothermoelasticity also regards the airframe and the airframe-propulsion integration. For the latter, six airframe-propulsion integration (API-) types are defined in this book. All plays a deciding role also in the final flight-vehicle certification. The API-type plays an important role also regarding flyability and controllability of the airbreather under consideration.

All in all it must be emphasized that it is not sufficient to create the concept of an airbreathing hypersonic aircraft or that of a globe-spanning airbreathing hypersonic cruiser. The topics design, development, ground testing, verification and finally certification before commission into service begins, are of eminent importance. Hence this book is dedicated to a sketch of relevant flight vehicle design, development and engineering issues. That to a degree is incomplete, in fact even lacking important details of some phases.

In view of the urging environmental challenges one has to ask whether—civil—airbreathing hypersonic flight should still be a worthwhile topic. There are at least three answers. (1) With TSTO-systems using LH2 as propellant it could be possible to reduce the environmental impact of launch to orbit in comparison to pure rocket launch. (2) The access to space with a TSTO-system from places far in the north, which was the rationale of the German Hypersonics Technology Programme in the 1980s/1990s, is a viable reason to pursue airbreathing hypersonic flight. (3) Long-haul hypersonic passenger flight, which however, appears to be problematic in view of the said environmental impact.

Regarding the design and development of hypersonic airbreathers a large number of phenomena and problems is present, which are not existing in ordinary aircraft design. Particular problems exist with the available simulation means. The designer must be aware of the potentials and the shortcomings of both the computational and experimental tools and facilities. This mainly regards the fields of aerothermodynamics, propulsion and structural mechanics.

Since the early 1980s, when airbreathing hypersonic flight became an interesting topic, disciplinary and multidisciplinary computation and optimization made marvelous developments. The second "mathematization wave" did happen. That was due to the enormous developments of computer power and storage and to the same degree due to the very impressive progress in the field of numerical algorithms. Experimental simulation with its opto-electronic measurement techniques also flourished thanks to the computer power and storage capabilities, which became available.

Computational flow simulation allows to treat steady and unsteady flow fields past and through configurations of all kinds, including surface radiation cooling—which is the permitting factor of hypersonic flight from the structural side—and thermo-chemical phenomena. Movable surfaces as well as aerothermoelastic deformations can be handled, and in particular also heat-transfer phenomena, both by conduction and radiation.

Laminar and attached turbulent flow can well be treated, surface irregularities can be modeled to a degree. The major unsolved problem is laminar-turbulent transition. The location, the shape and the extent of the transition zone has a very high impact regarding viscous flow phenomena and thermal loads. Separation of turbulent flow can be modeled with scale-resolving methods.

Combustion modeling in ramjet and in particular in scramjet engines faces the problem of turbulent mixture and ignition due to the very short residence times. The following expansion through the exhaust nozzle with thermo-chemical freezing effects can be handled.

Experimental flow simulation is well advanced, the quiet wind tunnel technique permits extremely important research and high-speed opto-electronic diagnostic techniques allow high-resolution insight into flow phenomena. Regarding hypersonic flow the big problems are that surface radiation cooling cannot be simulated experimentally, and that the disturbance environment of laminar-turbulent transition cannot be represented to the needed degree. With high Mach numbers, small model sizes and very short flow residence times over the model, the resulting diminutive measurement times are another limitation.

Structural mechanics faces a scale of thermal loads, which is not present in low-speed aircraft. Temperatures range from the cryogenic ones in fuel tanks and parts of the ram or scram engine to those of the radiation cooled surfaces of the external flow path over the flight vehicle. They may reach significantly more than 2000 K. It must be emphasized that, in the first place, only surface radiation cooling of the external flow path makes hypersonic flight of any kind possible by keeping surface and structure temperatures in the limits of available structural material. In the internal flow path, in particular in the engine's combustion chamber, even higher temperatures are present. Active cooling is a necessity there.

As a consequence, depending on the maximum flight speed and its duration, different materials, ranging from metallic to ceramic ones, become necessary. Subcritical surface imperfections are required, as well as a coating, which permits effective surface radiation cooling along the external flow path, and in general a low surface catalycity and anti-oxidation properties. Aerothermoelasticity plays a large role. Depending on the kind of airframe-propulsion integration—we distinguish five types of them—it can be a deciding factor regarding the flyability of the vehicle.

One problem of very high importance is that the mandatory dynamic structural tests of the assembled airframe with a hot primary structure at true flight temperatures appear not to be possible. That of course depends on the overall size of the flight vehicle, which in some studies goes up to nearly 100 m in length. A computational simulation is not possible because of the joint-modeling problem, which appears far from being solved. Joint modeling brings in scale/simulation problems comparable to the scale problem of turbulent flow.

Ground testing at true flight temperatures of the fully assembled propulsion system—from the inlet through the engine as such to the nozzle—of large hypersonic airbreathers extending over up to 30 m length also appears not to be feasible with the required means and facilities.

In both cases, ways to overcome these problems must be found and have been proposed, for instance, with the Hypersonic Technology Development and Verification Concept of the former German Hypersonics Technology Programme.

Regarding flyability and controllability of hypersonic airbreathers, a range of other items play a large, even deciding role, but are not addressed.

This sketch of design and development issues of hypersonic airbreathers shows the range of topics, which are treated in this book. However, by far not all is discussed in depth. Some general design problems are identified and illustrated but solutions are not discussed in detail. The book rather aims for an introduction into the field.

Overall, very little material from design studies is available, most from the former German Hypersonics Technology Programme. Regarding winged re-entry flight the "Lessons Learned" from the Space Shuttle Orbiter's first five flights, edited by J. P. Arrington and J. J. Jones (NASA CP-2283 (1983)), give a very valuable summary of technical details. For airbreathing hypersonic flight it is more or less only the book "Road to Mach 10—Lessons Learned from the X-43A Flight Research Program" by C. Peebles (Library of Flight, AIAA, Reston, Va. (2008)) with the 29 technical papers in the annex, which conveys much of the gained knowledge.

The authors of this book worked for almost five decades in different fields of hypersonics: at the German Aerospace Research Establishment (DVL/DFVLR, now DLR), in industry (MBB/Dasa, now Airbus), Industrieanlagen-Betriebsgesellschaft (IABG)), and in research and teaching at the Technical University Aachen (RWTH), the Technical University München (TUM), the University of the Armed Forces München and the University Stuttgart. They were involved in many major technology programs and projects of winged re-entry flight and hypersonic airbreathing flight.

The book is intended for graduate students, doctoral students, design, and development engineers, and technical managers. We believe that airbreathing hypersonic flight has a bright future. We hope that our book will help the reader to familiarize oneself with a number of problems and approaches regarding the design and development of airbreathing hypersonic flight vehicles.

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# Contents

# Chapter 1
# Introduction

Hypersonic airbreathers in the context of this book are winged and also non-winged hypersonic flight vehicles with either ramjet or scramjet (supersonic combustion ramjet) propulsion. This of course implies turbojet propulsion for the domains of subsonic, transonic and supersonic flight Mach numbers. The exceptions are the launch from a carrier aircraft and/or with a booster rocket used in the first stage of flight.

The intent of the book is to give the reader an outline of the major design and development issues of airbreathing hypersonic flight vehicles. It is not intended to give solutions to particular design problems, but to identify those, to show their importance and to give reference to the pertinent literature and to further reading. Very important is to realize that the design and development issues of such flight vehicles basically are different compared to those of winged or non-winged re-entry vehicles.

Predominantly we consider flight vehicles, which start from the ground. Much of the content of the chapters of course also holds for other launch modes.

In the following Sect. 1.1 we give an overview of studies and projects of airbreathing hypersonic flight. Section 1.2 then looks at three classes of hypersonic flight vehicles of which the cruise and acceleration vehicles (CAVs), and the ascent and re-entry vehicles (ARVs) are the topic of this book.

A short historical survey of ramjet and scramjet propulsion is the topic of Sect. 1.3. Four key technologies and five types of airframe-propulsion integration are considered in Sects. 1.4 and 1.5. Particular development problems, namely requirements creep, obsolescence and mass issues, which are of high significance especially for airbreathing hypersonic flight vehicles, are looked at in Sect. 1.6. Closing the introduction a short overview is given over the contents of the chapters of the book.



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## 1.1 Airbreathing Hypersonic Flight: Overview of Studies and Projects

Airbreathing hypersonic flight, i.e., airbreathing flight at Mach numbers $M_\infty \gtrapprox 5$, see Sect. 2.1.1, became a possibility with the maturation of ramjet and later scramjet propulsion, Sect. 1.3. Ramjet propulsion first concerned mainly military applications and later space transportation systems, whereas presently military scramjet applications are emerging worldwide. This section gives a short overview of the projects and the achievements so far. A global overview and a look in particular at European efforts up to about the year 2011 is given in [1]. That mainly concerns re-usable space transportation systems with single-stage-to-orbit (SSTO) systems and the lower stages of two-stage-to-orbit (TSTO) systems.

In 1986 US President Ronald Reagan was asking for an *Orient Express*, which with a flight Mach number $M_\infty = 25$ would permit to reach low Earth orbit or to fly from Dulles Airport in Washington DC to Tokyo in about two hours. That call led to a number of proposals and work on SSTO-systems—and on airbreathing propulsion systems—such as the National Aerospace Plane (NASP), with the technology demostrator X-30. NASP was finally abandoned due to unsurmountable problems with the hydrogen-fueled ram/scramjet propulsion system, airframe-propulsion integration, and the structure and materials concept. The program was canceled in 1993.

In Europe at that time a number of proposals, system and technology studies and also projects with airbreathing first stages of TSTO-systems and airbreathing/rocket SSTO-systems was initiated and finally also terminated [1].

In the U.K. it were SSTO-concepts, first the Horizontal Take-Off and Landing concept HOTOL, which was pursued from 1982 to 1988, followed by the Interim HOTOL and finally the SKYLON concept, which was terminated in 2016.

In France, beginning around 1986, several TSTO- and SSTO-concepts were studied, for instance the SSTO-system ORIFLAMME, and the TSTO-systems RADIANCE and STAR-H. Finally all converged into the program PREPHA in the period 1992 to 1996. That basically was a research and technology program on hypersonic scramjet propulsion investigating topics like operation and flight-vehicle integration, computational tools for aerothermodynamics and combustion, and others.

Germany, from 1987 to 1995, had the Hypersonics Technology Program with the TSTO-reference concept SÄNGER [1], see also [2]. Studied also were several hypersonic technology experimental aircraft versions under the name HYTEX [1]. In the field of aerothermodynamics a cooperation with Norway and Sweden started in 1990. Three Collaborative Research Centers, funded by the Deutsche Forschungsgemeinschaft (DFG) at Aachen, Stuttgart and Munich together with the German Aerospace Center (DLR) worked on related topics, with the TSTO-system ELAC as reference concept [3].

The European Space Agency (ESA) initiated the Future European Space Transportation Investigations Program (FESTIP), which lasted from 1994 to 1998 [1]. Conceptual design work was performed for 18 system concepts, only two were

TSTO-systems with an airbreathing lower stage. The integrated international concept team had also some experts from Russia.

Since the beginning of the 1980s special efforts were spent on the advancement of scramjet technology. NASA and CIAM performed flight tests over the Soviet Union. Later also France joined in, see, e.g., [4, 5]. The four HyShot flight tests—with hydrogen as propellant—in Australia, performed by the University of Queensland with different international partners, were dedicated to supersonic combustion experiments, see, e.g., [6, 7]. HyCAUSE, i.e., Hypersonic Collaborative Australian/United States Experiment, was a flight experiment with a configuration with a three-dimensional inward-turning inlet, in contrast to the usually two-dimensional inlet [8].[1] The flight on June 15, 2007, which was to reach $M_\infty = 10$, was not successful.

The program Hyper-X of NASA was to demonstrate the performance of a hydrogen-propelled scramjet integrated into an aircraft. Three flight tests of the X-43A were attempted, the first one failed, in March 2004 with the second one $M_\infty$ = 6.83 was reached, and with the third one finally $M_\infty = 9.68$ in November 2004, [9, 10], see also Sects. 5.1.1 and 6.4.

Hyper-X was the first of hypersonic flight vehicles in the Next Generation Launch Technology (NGLT) program of NASA [11]. NGLT had the goal to advance hypersonic airbreathing vehicle system technologies in view of future space launch systems in general. In the meantime military applications in the form of hypersonic cruise missiles with scramjet propulsion became an urgent topic. Worldwide efforts started to develop corresponding systems for the low hypersonic Mach number domain around $M_\infty \approx 5$ to 6.

In the years 2003 to 2010 in HyFly a dual-combustion ramjet (DCR), i.e., a ramjet with a combustion chamber for both subsonic and supersonic combustion and with a circular inlet, was tested. HyFly, funded by the U.S. Navy and DARPA, was to investigate the technology of a hypersonic tactical guided ramjet missile with jet propellant JP-10 [12]. Several flight tests were performed, the last one in the year 2010, but none led to a full success. In the year 2020 the DCR technology again became a topic of interest with the hypersonic cruise missile designated HyFly 2.

The waverider X-51A of the US Air Force on May 26, 2010 performed the, until then, longest hypersonic flight of a scramjet propelled vehicle [13]. The flight with the Mach number $M_\infty = 5$ lasted 210 s. The propellant was JP-7, which also was used to cool the scramjet engine.[2] The attempt on June 13, 2011 to reach $M_\infty = 6+$ failed due to inlet unstart.

In the Soviet Union already in the 1960s a TSTO-system, the Spiral 50–50, with an airbreathing lower stage was pursued. In the 1990s in the Oryol program the TSTO-system MIGAKS with an airbreathing lower stage was investigated. Military developments followed. In the year 2020 Russia claimed to have reached $M_\infty = 8$ with the cruise missile 3M22 Zirkon. Its NATO code for the ship-based version is SS-N-33 Zirkon.

[1] We use the notation 'inlet' instead of 'intake'.

[2] For the implications of JP-7 see Sect. 2.6.

**Table 1.1** Technology readiness levels (NASA)

| | |
|---|---|
| TRL 1 | Basic principles observed and reported |
| TRL 2 | Technology concept and/or application formulated |
| TRL 3 | Analytical and experimental critical functions and/or characteristic proof of concept |
| TRL 4 | Component and/or breadboard validation in laboratory environment |
| TRL 5 | Component and/or breadboard validation in relevant environment |
| TRL 6 | System/subsystem model or prototype demonstration in a relevant environment (ground or space) |
| TRL 7 | System prototype demonstration in a space environment |
| TRL 8 | Actual system completed and "flight qualified" through test and demonstration (ground or flight) |
| TRL 9 | Actual system "flight-proven" through successful mission operations |

The European Union funded the Long-Term Advanced Propulsion Concepts and Technologies (LAPCAT) study, coordinated by ESA-ESTEC. It followed ATLAS-I, ATLAS-II, FAST20XX, HEXAFLY and STRATOFLY. LAPCAT I lasted from the years 2005 to 2008 with 12 partners from industry, research institutions and universities. LAPCAT II followed from 2008 to 2012, HEXAFLY-INT from 2014 to 2019 and STRATOFLY from 2018 to 2020. The overarching objective of these studies and projects was to advance the technology of airbreathing hypersonic flight in view of possible future antipodal connections [14–16], similar to the aforementioned Orient Express concept of the U.S. It is expected that the Technology Readiness Level TRL = 6, Table 1.1, can be reached by the year 2035 for hypersonic transatmospheric flight.

In the last couple of years there was seen a worldwide turn of airbreathing hypersonic flight toward hypersonic cruise missiles, presently with ramjet propulsion only. Such missiles, together with boost-glide vehicles, the latter without propulsion unit, today pose the largest technological challenges of flight-vehicle development.

Sustained hypersonic flight capability for future military applications already was a topic at NATO in the 1990s [17]. Considered were long range immediate-reaction reconnaissance, high speed interception of air targets, long range precision strike against hardened and/or time critical targets, and also access to space. As strategic benefit was seen the inherent reduction in time-to-target and low vulnerability.

It can be expected that in the future a technological spillover from present military applications to civil hypersonic flight, also to TSTO- and SSTO-systems may happen.

## 1.2 Hypersonic Flight Modes and the Related Flight Vehicles

When speaking of hypersonic flight—we only treat flight in the Earth's atmosphere—one has to distinguish between at least three modes and the associated classes of flight vehicles. The different modes lead to different configurational and multidisciplinary design and development problems and also to different flow-physical challenges.

The three flight modes are re-entry flight, cruise and acceleration flight as well as ascent and re-entry flight. Accordingly we speak of re-entry vehicles (RVs), cruise and acceleration vehicles (CAVs), and ascent and re-entry vehicles (ARVs).[3] The latter two vehicle classes are the topic of this book.

Re-entry vehicles (RVs)—we consider only re-entry flight from low Earth orbit (LEO)—are either non-winged vehicles, i.e., capsules, or winged vehicles. Capsules are in operation from the 1960s on and presently dominate the field. Winged re-entry vehicles are the former US Space Shuttle Orbiter, the Russian BURAN with only one flight, the abandoned European HERMES project, the abandoned European-US X-38 project, the abandoned Japanese Hope-X project, the abandoned German HOPPER project, and presently the active Boeing X-37 and the Dream Chaser of the Sierra Nevada corporation. Their common mission is an aero-braking flight from LEO to the Earth surface. Characteristic features of this vehicle class are listed in the second column of Table 1.2.

Cruise and acceleration vehicles (CAVs), third column of Table 1.2, are flight vehicles with airbreathing propulsion, which encompasses turbojet modes, ramjet modes, and scramjet modes. These vehicles, up to recent times were mainly in the conceptual phase. Cruise vehicle means air-transportation flight, whereas acceleration flight means flight of, for instance, lower stages of two-stage-to-orbit (TSTO) space transportation systems, up to the separation of the upper orbital stage.

The third vehicle class, ascent and re-entry vehicles, (ARVs), includes single-stage-to-orbit vehicles (SSTO) with either airbreathing propulsion or mixed air-breathing/rocket propulsion, fourth column of Table 1.2. Also here airbreathing vehicle developments remained at the conceptual level. Examples are, for instance, the US American National Aerospace Plane (NASP) or X-30 and the British HOTOL.

The difference between the first two vehicle classes is evident when considering their missions. Because RVs basically fly a braking trajectory, they have a blunt shape in order to achieve a high aerodynamic drag. This is evident when looking at capsules, which however fly at a small angle of attack in order to allow for trajectory corrections on a limited scale, see, e.g., [19]. Winged re-entry vehicles have a blunt nose, and blunt leading edges, too. In addition, in the high Mach number regime they fly at a high angle of attack. With the Space Shuttle Orbiter that was around $\alpha = 40$.

[3] In [18] as well as in [19] the terms *re-entry vehicle* (RV), *cruise and acceleration vehicle* (CAV) and *ascent and re-entry vehicle* (ARV) are used, and are employed here, too.

**Table 1.2** Comparative consideration of the aerothermodynamic features and multidisciplinary design features of three major classes of hypersonic vehicles

| Item | Re-entry vehicles (RV's) | Cruise and acceleration vehicles (CAV's) | Ascent and re-entry vehicles (ARV's) |
|---|---|---|---|
| Mach number range | 28–0 | 0–7 to 12 | 0 to 7/12–28 |
| Configuration | Blunt | Slender | Opposing design requirements |
| Flight time | Short | Long | Long(?)/short |
| Angle of attack | High | Low | Low/high |
| Drag | High | Low | Low/high |
| Aerodynamic lift/drag ratio | Low | High | High/low |
| Flow field | Compressibility-effects dominated | Viscosity-effects dominated | Viscosity-effects/ compressibility-effects dominated |
| Laminar-turbulent transition | Important | Very important | Opposing situations |
| Thermal surface effects: 'viscous' | Not important | Very important | Opposing situations |
| Thermal surface effects: 'thermo-chemical' | Very important | Important | Opposing situations |
| Thermal loads | High | Medium/high | Medium/high |
| Thermo-chemical effects | Strong | Weak/medium/strong | Medium/strong |
| Rarefaction effects | Initially strong | Weak | Medium/strong |
| Critical components | Trim and control surfaces | Inlet, nozzle/after-body, trim and control surfaces | Inlet, nozzle/afterbody, trim and control devices |
| Special problems | Large Mach-number span | Propulsion integration, thermal management | Propulsion integration |

LEO re-entry vehicles of either kind usually have a cold primary structure and a passive heat protection system, Sect. 6.1. Cooling is via surface radiation, Sect. 3.8, which means that a surface coating besides the anti-oxidation and anti-recombination properties needs to have a high radiative emissivity, which gives the windward oriented surfaces a near-black appearance. The emissivity coefficient is around $\epsilon \approx 0.8$ to 0.9. A winged re-entry vehicle has a low emissivity lee-side coating of near white appearance in order to allow to manage in orbit the heat radiated from the sun, see the former Space Shuttle Orbiter, the X-37 and the Dream Chaser.

CAVs in contrast to RVs need to have a small aerodynamic drag to accelerate and/or cruise at high speed through the atmosphere. This leads to slender configurations with small nose and leading-edge radii, which fly at small angle of attack. They may have a hot primary structure, however, with the requirement to house cryogenic fuel tanks. The vehicle surface including the lee side is radiation cooled. Contradictive requirements exist at the vehicle's nose and leading edges, Sect. 3.5. They need to have small radii in view of the aerodynamic wave drag, but sufficiently large radii in order to allow for radiation cooling that needs large boundary-layer thicknesses. Usually this leads to ceramic materials for these vehicle surface elements, Chap. 6.

We distinguish six basic types of airframe-propulsion integration (API), Sect. 1.5. With the API-types 4 and 5, up to now the most prominent ones, the lower side of the vehicle houses the propulsion system including the inlet and the nozzle. The latter cannot be a bell nozzle, because tail striking at the high angles of attack during take-off and approach and landing must be avoided. The nozzle either can be a single expansion ramp nozzle (SERN) or a linear spike nozzle. The lower side of the flight vehicle hence is a highly coupled lift and propulsion system. Demanded is a configuration with a low-drag aerodynamic shape that ensures flyability and controllability in the entire flight envelope.

These short characterizations reveal the contradicting demands on the third vehicle class of Table 1.2, the ascent and re-entry vehicle (ARV) class. To reach orbit with purely airbreathing propulsion, as was the approach with NASP, certainly is a pipe dream. For an ARV the whole sequence of turbojet, ramjet/scramjet and rocket propulsion appears to be the only possibility to reach LEO. And that certainly is far away into the future, if it is possible at all, given the different design characteristics.

## 1.3 Ramjet and Scramjet Propulsion

The literature on ramjet and scramjet propulsion systems is immense. Here we give a short overview only, pointing in particular to [20]. Turbojet propulsion came into practical application during the 1940s. The concept of ramjet propulsion goes back to Ren Lorin, who in 1913 made a proposal in this regard. Whether the propulsion system of the German Fieseler Fi 103, the V-1 flying bomb, called Vengeance Weapon 1, can be considered as a ramjet, is arguable. A true ramjet propelled flight vehicle was devised by Ren Leduc in France, and supersonic speeds were achieved in 1957 with the Nord Aviation Griffon II, which had turbojet/ramjet propulsion.

Supersonic missiles with ramjet propulsion, which have to start with a rocket booster, were studied worldwide during and after the Second World War and reached practical application. In the 1950s the scramjet, a ramjet with supersonic combustion, came into consideration. In the hypersonic flight regime the pure ramjet concept leads to very high pressures and temperatures in the engine, which can no more be handled.

The supersonic combustion ramjet, the scramjet, is the way out. In the whole flow path through the engine supersonic flow is present. Thus avoiding the high pressure and temperature, which would result if the flow is decelerated to subsonic flow. This of course goes together with the tremendous challenge to achieve combustion in a supersonic flow with a very short residence time of the flow in the engine's combustion chamber.

Whereas ramjet propulsion is a well understood propulsion mode, scramjet propulsion for hypersonic flight, i.e., at flight Mach numbers $M_\infty > 5$, more or less is in its infancy. The flights of the X-43A with $M_\infty = 6.83$ in March 2004 and $M_\infty = 9.68$ in November 2004 and that of the X-51A with $M_\infty = 5$ in 2010 were milestones. These flights were more or less design-point flights, the question of off-design operation appears not to have been answered. Not much is known about the Russian Zirkon cruise missile, for which a maximum Mach number of 8 is claimed. In general it appears that presently military applications are driving the scramjet technology worldwide.

When we talk about a flight vehicle with scramjet propulsion, for instance a CAV, we tacitly mean a propulsion system, which consists of a turbojet component, a ramjet, and a scramjet component. These components can come as mixed components, for instance a turboramjet or a ram-/scramjet (Dual Mode Ramjet (DMR)). Except for Chap. 4, where we treat basics of ramjet and scramjet propulsion, we simply speak of ramjet or scramjet propulsion, without reference to the turbojet and/or mixed systems. The latter may include also rocket propulsion either for the launch regime or the high speed regime of launch into orbit.

The detonation engine as propulsion means is a topic since the 1940s. It is a possible engine concept for hypersonic flight. Despite extensive research efforts no application is known up to now. In [21–23] detailed information can be found.

## 1.4 Key Technologies

The key technologies treated in this book are aerothermodynamics, propulsion, structure and materials, and control and guidance.

- Aerothermodynamics provides via airframe shaping and optimization the lift and with that the flyability and controllability of the flight vehicle while aiming to keep drag within acceptable limits. Along the vehicle's external flow path it further gives the mechanical loads—surface pressure and skin friction—and in particular also the thermal loads—temperature and heat flux—on the airframe. A special topic is airframe-propulsion integration, which depends on the airframe-propulsion integration (API-) type, see Sect. 1.5. Chapter 3 is devoted to an overview of the field of aerothermodynamics as a design technology.
- Propulsion has to cover the whole flight Mach-number span of the vehicle. That regards the core engines of turbo, ramjet and, if applicable, scramjet propulsion in their different combinations. Exceptions are—primarily—military applications with rocket booster for launch. The link to aerothermodynamics is via the external and in particular the propulsion flow path with the inlet system and the isolator—the duct between inlet and combustor—the combustor and finally the exhaust nozzle. The latter, depending on the type of airframe-propulsion integration—see below—can be a single expansion ramp nozzle (SERN), a bell nozzle (not likely an option for CAV-type vehicles), a plug nozzle or a linear spike nozzle. Major

aspects of ramjet and in particular scramjet propulsion are treated in Chap. 4. Chapter 5 deals with issues of airframe-propulsion integration.

- Structure and materials provide the airframe in view of the mandatory aerodynamic lift, stabilization, trim and control surfaces, the propulsion flow path, the internal volumes, the mechanical loads, and the thermal loads. The thermal loads topic has two challenges, the high temperatures present at the external surface and along the propulsion flow path, as well as the extremely low temperatures in the fuel system, if cryogenic fuel is used. The external flow path to a high degree has surface radiation cooling, whereas active cooling is mandatory for the internal (propulsion) flow path. All that is the topic of thermal management of the flight vehicle. Structure and materials are the topic of Chap. 6.
- Control and guidance is a field which supplements the above key technologies. Flight vehicle control is not only a topic of aerodynamic stabilization, trim and control surfaces, but also of the thrust-vector change with flight Mach number, if a single expansion ramp nozzle is employed. Guidance concerns the flight path of the aircraft in view of its mission including take-off and approach and landing, but also in view of the mechanical and thermal loads and the propulsion demands. A short characterization is given for instance in [19]. Critical elements are the air-data system, either as flush ports in the vehicle nose, or as opto-electronic system, for instance LIDAR, and the notch filters, which prevent the elastic airframe deformation fluctuations to enter and adversely affect the aircraft's flight control system.

## 1.5 Basic Types of Airframe-Propulsion Integration

The topic 'airframe-propulsion integration' directly governs the connections between the key technologies in the sense of Cayley's design paradigm, Sect. 2.2. Different integration types have emerged so far for hypersonic airbreathers, with different merits and different challenges.

A major effect is present, if forebody pre-compression is applied. That is used in order to reduce effectively the inlet capture area, but leads to a high net-thrust sensitivity depending on the angle of attack of the flight vehicle, Sect. 5.5.

Another effect is related to the SERN-type nozzles. These are necessary in order to avoid tail striking during take-off and approach and landing. Such nozzles however lead to changes of the thrust vector direction with changing flight Mach number, Sect. 5.7. Whether linear spike nozzles are a way out is not established.

There are many studies and projects regarding hypersonic flight vehicles. We tentatively select six basic Airframe-Propulsion Integration types (API-types), which are listed with increasing complexity. For the corresponding studies and projects see Sect. 1.1 above.

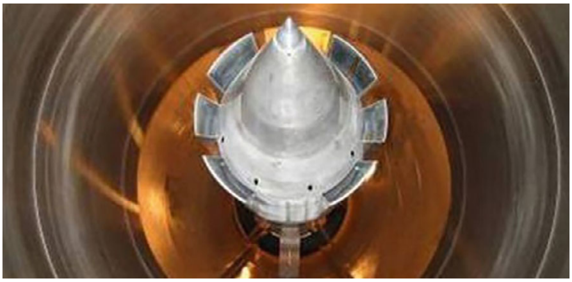

**Fig. 1.1** The HyFly circular inlet [24]

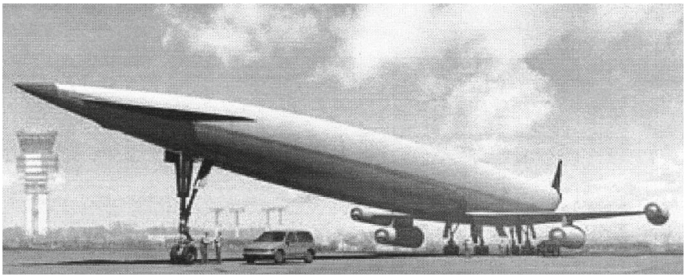

**Fig. 1.2** The LAPCAT-A2 configuration [14]

- API-type 0 has a circular inlet with a central cone, Fig. 1.1. The propulsion unit is also circular, the nozzle is a bell nozzle. Lift for this type is provided by wings. No direct coupling of the lift and the propulsion function is present.
  HyFly was a hypersonic cruise missile demonstrator with a dual-combustion ramjet. It was terminated. HyFly 2, the successor, also with a dual-combustion ramjet, is of API-type 3.
- API-type 1 has podded propulsion units for instance below the wing and at the wing tips, Fig. 1.2.
  This is an artist impression of the civil Mach 5 transport proposal studied in the LAPCAT program, with its origins in the SKYLON proposal. The flight vehicle with pre-cooled turbo-ramjet engines has a trapezoidal wing and a canard. There is no interaction between the fuselage plus the wing and the circular inlets of the loosely integrated propulsion units. Provided that sufficient ground clearance is given through take-off and landing, the nozzles are bell nozzles. Aerothermoelastic wing behavior will affect the engines in particular those at the wing tips.
- As API-type 2 the study STRATOFLY MR2/MR3 can be seen, Fig. 1.3.
  It has a waverider configuration with an inward-turning inlet on the upper side, like the HyCAUSE vehicle [8]. The propulsion flow path with three compression ramps, the isolator, the combustor chamber, and the bell nozzle is completely inside the airframe. Lift generation at the lower side of the aircraft hence is decoupled from the thrust generation.

**Fig. 1.3** STRATOFLY MR2 with inward turning inlet [16]

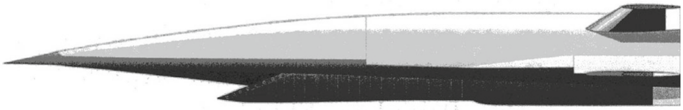

**Fig. 1.4** X-51A as example of an API-type 3 flight vehicle [25]. Short pre-compression surface, $L_{pc} \approx 2\,\text{m}$, no SERN, bell nozzle

- API-type 3 appears to be typical for present-day hypersonic cruise missiles. Examples are the waverider X-51A, Fig. 1.4, HyFly 2, and the SS-N-33 Zirkon.
  The inlet is at the lower side of the flat forebody, which serves as short pre-compression (pc) surface, like with API-type 4 vehicles.[4] The flat forebody up to the first inlet ramp acts as pre-compression surface, reducing the inlet capture area—the inlet is a two-dimensional one—of the propulsion unit.
  The missiles, launched for instance with a rocket booster, have bell nozzles, because there is no need to approach and land horizontally. With a bell nozzle no thrust-vector change happens along the flight trajectory. If the nozzle is a swivel nozzle, used for trajectory changes/corrections, the deflections will be small. In any case the nozzle will not have the consequences, which a SERN-type nozzle has.
- API-type 4 flight vehicles also have the inlet at the lower side with a short forebody pre-compression surface. An example is the X-43A, Fig. 1.5. The X-43A as experimental flight vehicle with scramjet propulsion was the first to reach high hypersonic flight Mach numbers. Lift generation and propulsion happens at the lower side of the flight vehicle, see the API-type 5 characterization.
  Another example is the Lockheed SR-72, where the inlets—left and right side—are at the wing roots and parts of the forebody and the wing surface act as pre-compression surfaces. Aerothermoelasticity effects seem not to play a significant role. The nozzle maybe of SERN type (X-43A) or a round or rectangular one (SR-72).

[4] Forebody: short and long, both as absolute measures, are qualitative statements related to whether major aerothermoelastic effects are to be expected.

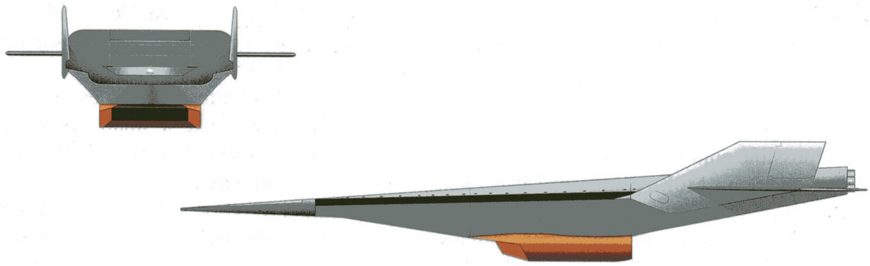

**Fig. 1.5** Example of an API-type 4 flight vehicle: NASA's X-43A, short pre-compression surface, $L_{pc} \approx 0.95\,\text{m}$, SERN [25]. Upper left: front view, lower middle: side view

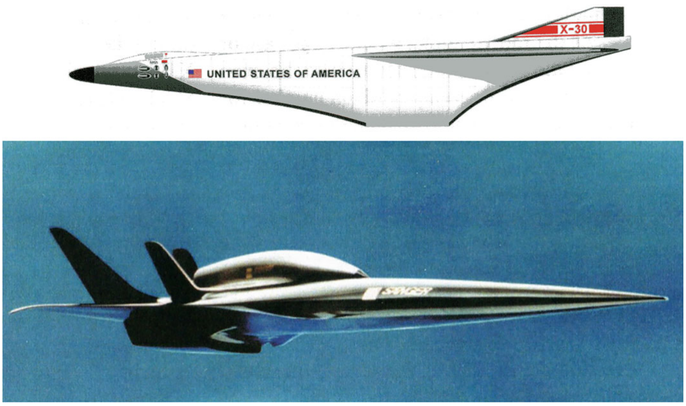


**Fig. 1.6** Examples of API-type 5 flight vehicles (long pre-compression surface, SERN). Upper part: the SSTO-system NASP/X-30 [25], $L_{pc} \approx 16\,\text{m}$. Lower part: the lower stage—with the upper stage mounted—of the TSTO-system SÄNGER of the German Hypersonics Technology Programme [1], $L_{pc} \approx 52\,\text{m}$

- API-type 5 to a degree can be considered as a classical way of hypersonic airframe-propulsion integration with the lower side of the forebody being a long pre-compression surface. NASP/X-30, configuration 201, 1990, upper part of Fig. 1.6, as well as the lower stages of TSTO-concepts in the 1980s and the 1990s were of this type. The lower stage of the SÄNGER TSTO-system, lower part of Fig. 1.6, is also an example.
  The propulsion unit is located at the lower side of the flight vehicle. The long slender forebody minimizes the wave drag. It further provides the needed volume for fuel tanks and so on. The nozzle is of SERN type in order to permit rotation of the aircraft during take-off and approach and landing. Wings are necessary in order to provide additional lift and to assure low-speed flight qualities, see, e.g., [26].
  The lower side of the flight vehicle thus serves for both, lift generation and propulsion. Cayley's design paradigm, Sect. 2.2, hence is invalid. Problems associated

**Table 1.3** Airframe-Propulsion Integration types and their characteristic complexities

| Integration type | Characteristic complexities |
|---|---|
| API-type 0 | Cylindrical missile body, lift is provided by wings. Circular inlet, bell nozzle, no lift-propulsion interaction |
| API-type 1 | This type has podded engines like a transport aircraft. Circular inlets. Aerothermoelastic challenges arise with wing-tip engines, hence a coupling of lift and thrust will be a problem |
| API-type 2 | Engine-onset flow is fully inside the body, the nozzle is of bell type. Inward turning rectangular ramp inlet. No coupling into lift and pitching moment |
| API-type 3 | This missile type has a flat lower-side forebody, serving as pre-com-pression surface and a bell nozzle. Rectangular ramp inlet. Coupling of lift and propulsion system |
| API-type 4 | Short forebody lower-side pre-compression and possible SERN result in coupling of lift and thrust. Rectangular ramp inlet. With large flight vehicles aerothermoelastic effects of the relatively short forebody lead to a certain net-thrust sensitivity |
| API-type 5 | Long forebody lower-side pre-compression and SERN result in high coupling of lift and thrust. Rectangular ramp inlet. Aerothermoelastic effects of the long forebody lead to a high net-thrust sensitivity |

with this type of integration are aerothermoelasticity effects, the wall-temperature difference between the lower and the upper side, the net-thrust sensitivity and the thrust-vector change of the SERN-type nozzle. Similar issues—except for the forebody aerothermoelastic effects—arise with API-type 4 flight vehicles.

These types of airframe-propulsion integration pose different problems regarding the four key technology fields sketched in the preceding Sect. 1.4. A major technological problem arises with the coupling of lift and propulsion. The coupling is zero with API-type 0, low with type 1, followed with some distance by type 2 and 3 and highest with type 4 and in particular type 5.

Of importance too is the inlet performance in terms of cross-section reduction and total-pressure recovery. This is discussed in Sect. 5.2.

In Table 1.3 the API-types are listed together with their characteristic complexities.

## 1.6 Particular Development Problems

Development of new and technologically highly advanced flight systems can take many years, even decades. The development of the Space Shuttle took about nine years until the first mission was flown. The fighter aircraft F-35 needed 14 years until entry into service (EIS). About ten years into EIS were needed with the passenger aircraft B787 and A350.

With long development times—but not necessarily only with them—at least three problems arise and have to be taken care of: requirements creep, obsolescence, and mass increase. They all affect the iron triangle “performance, cost, schedule”.

Requirements creep means that the requirements on the product change with time, a problem more typical with military products. The tactical or the strategic setting changes with time and the customer reacts with new or modified requirements. In any case development time and cost will rise, sometimes even dramatically. The same holds for hypersonic airbreathers with their long technical maturation and development times, for the X-43A see, e.g., [10].

Obsolescence of devices, materials and general approaches is a possibility in particular with very advanced projects, which take long times to develop. Take for instance a new highly advanced material for high-temperature application which makes existing materials obsolete. Change in a late stage of development may require a revamping of the design. If accepted, costs will rise and the EIS will be shifted.

Mass increase of the airframe and/or the propulsion system during the design and the development phase of aircraft is a common fact. It often happens also during the opening of the flight envelope. A particular problem too, is the location of the center of gravity. Its position relative to the center of pressure determines stability and control requirements of the aircraft, see, e.g., [27]. Regarding the longitudinal stability, ballast in the fuselage nose or a change of the sweep angle of the wing are means of correction.[5] Tuning of the aeroelastic properties of wings with ballast can also become necessary.

For modern passenger aircraft with matured, metal-construction technology the dry mass empty increase up to EIS is usually below 2%. For composite airframes no data are yet publicly available. Commercial passenger aircraft have structural weight fractions of about 20%.

The mass increase during an aircraft development and envelope opening phase is taken into account with the so-called contingency mass. This mass margin is defined already in the flight-vehicle definition phase. In the design of fighter aircraft one today assumes a contingency mass of about 6 to 8% of dry-mass empty. From the first flight to full mission deployment another 2 to 4% mass growth are a rule.

For the TSTO system SÄNGER, Sect. 2.8, the payload/dry-mass empty ratio was 4.4% related to the lower stage, and 2.5% related to the whole TSTO system, see, e.g., [29]. The contingency mass both for the lower stage and for the whole system, was only 3.1% of dry-mass empty. This was much too optimistic. For a large air vehicle of this kind and for the propulsion and speed domain, even today only insufficient design and operation experience is available.

[5] Early German examples of sweep-angle correction are for instance (a) the wing of the Focke-Wulf Fw 200 Condor, where the outer wing portions had to be swept back by about 7°, and (b) the Messerschmitt Me 262, where the wing was swept back from original 4° to 18°. This still leads to the wrong impression that from the beginning the aircraft was a swept-wing aircraft. Later versions of the aircraft with truly swept wings were studied, which finally led to the pioneering P 1101 V-1 project, see, e.g., [28].

## 1.7 The Content of the Chapters

The following Chap. 2 discusses hypersonic airbreather design on a basic level. The differences to the design of conventional aircraft are highlighted, Trends and sensitivities are emphasized. In the next four chapters major technologies are discussed: aerothermodynamics, propulsion, airframe-propulsion integration, and structure and materials.

Chapter 3 treats the aerothermodynamic features of the external flow path, in particular high temperature real-gas effects, the thermal state of the vehicle surface and for the considered flight vehicles the extraordinarily important problem of laminar-turbulent transition. General design considerations are given and the stage integration as well as the separation process of TSTO concepts are examined.

Ramjet and scramjet propulsion are the topic of Chap. 4. The basic features of scramjet propulsion are discussed. Airframe-propulsion integration is treated in Chap. 5. Accounting of forces and moments is considered as well as forebody pre-compression and the ensuing sensitivities. Inlet and nozzle (SERN) topics are treated, also coolant flow, and the interactions of the propulsion system with the flight vehicle's trim and control.

Chapter 6 looks at structure and materials aspects, hot and cold structures, the latter with a thermal protection system, all with the respective materials, fuel-tank integration and so on. The overall problem of aerothermoelasticity is addressed.

Technology development and verification is considered in Chap. 7. Experimental ground-testing facilities, computational simulation, and also experimental flight vehicles are examined and possible Technology Development and Verification (TDV) approaches discussed. Chapter 8 sketches the German Hypersonics Technology Development and Verification Concept. Closing notes are given in Chap. 9.

In all following chapters problems are given with a solution guide and the solutions provided in Chap. 10. Properties of the Earth standard atmosphere are given in Appendix A.

Constants, functions etc. are listed in Appendix B. Symbols, abbreviations and acronyms are given in Appendix C. Copyrights of figures, a subject and a name index close the book.

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