Historical Perspective on Programs, Vehicles and Technology Issues

E. H. Hirschel
University Stuttgart and ex EADS Military Aircraft
Munich, Germany

1. Introduction

System definition and technology development and preparation for hypersonic flight is an ongoing process since about 60 years. However, only one operational flight vehicle, the U. S. Space Shuttle, has resulted so far. Nevertheless, much insight and an appreciable technology base has been created, and several experimental vehicles have flown and contributed to this. In this paper programs, vehicles and technology issues are considered concerning space-trans-portation systems and hypersonic flight vehicles in general. Purely military hypersonic flight systems are not taken into account. The discussion is organised along two flight-vehicle classes: aeroassisted re-entry vehicles (RV-type vehicles) and airbreathing cruise and acceleration vehicles (CAV-type vehicles), with little consideration of shades in between. The speed regime of these vehicles is below approximately 8.0 km/s at altitudes below approximately 100.0 km.

The paper is organised such, that after the classification of vehicles air-vehicle engineering issues are discussed with an overview over the requirements on the technical disciplines and a consideration of some special issues of CAV-type vehicles. Major programs and flight vehicles are then discussed, first of RV-type, then of CAV-type. Finally selected design and development issues from the HERMES and the SÄNGER work are treated and the implications of the second mathematisation wave in sciences and engineering for the design and development of hypersonic flight vehicles technology are discussed. Throughout the paper an air-vehicle engineering perspective is taken, technical disciplines are not considered in depth, except to a certain degree aerothermodynamics in its multidisciplinary context. Completeness is not attempted.

2. Classification of Hypersonic Flight Vehicles

Usually issues of hypersonic flight are discussed while not taking into account, that big differences exist between flight of pure re-entry vehicles and flight of airbreathing vehicles. It is, however, beneficial to define classes of hypersonic flight vehicles in view of their different design and technology features.

Following [1], we define four classes of hypersonic flight vehicles (a compilation of hypersonic flight vehicles will become available with [2], for the X-planes see [3]):

1. Winged re-entry vehicles (RV): Space Shuttle, BURAN, HERMES, ..., X-38, ...
2. Airbreathing cruise and acceleration vehicles (CAV): lower stages of TSTO systems, e. g., SÄNGER, hypersonic aircraft, ...

Paper presented at the RTO AVT Lecture Series on "Critical Technologies for Hypersonic Vehicle Development", held at the von Kármán Institute, Rhode-St-Genèse, Belgium, 10-14 May, 2004, and published in RTO-EN-AVT-116.

3. Airbreathing ascent and re-entry vehicles (ARV): NASP/X-30, HOTOL, ...
4. Aeroassisted orbital transfer vehicles (AOTV).

We use in the following chapters RV-type and CAV-type flight vehicles as reference classes. All shades in between are possible, e. g., ARV-type vehicles, Table 2.1. AOTV-type vehicles are included there as extreme case. Much more detailed classifications of hypersonic flight vehicles, including military ones, can be found in the literature, for instance in [4].

Each of the four classes has specific design and technology features and challenges, Table 2.1.

Table 2.1 Classification of hypersonic flight vehicles and comparative consideration of design and technology features [1].

Item	Re-entry vehicles (RV)	Cruise and acceleration vehicles (CAV)	Ascent and re-entry vehicles (ARV)	Aeroassisted orbital transfer vehicles (AOTV)
Mach number range	28 - 0	0 - 7(12)	0(7) - 28	20 - 35
Configuration	blunt	slender	opposing design requirements	very blunt
Flight time	short	long	long(?)/short	short
Angle of attack	large	small	small/large	head on
Drag	large	small	small/large	large
Aerodynamic lift/drag	small	large	large/small	small
Flow field	compressibility-effects dominated	viscosity-effects dominated	viscosity-effects/ compressibility-effects dominated	compressibility-effects dominated
Thermal surface effects: ’viscous’	not important	very important	opposing situation	not important
Thermal surface effects: ’thermo-chemical’	very important	important	opposing situation	very important
Thermal loads	large	medium	medium/large	large
Thermo-chemical effects	strong	weak/medium	medium/strong	strong
Rarefaction effects	initially strong	weak	medium/strong	strong
Critical components	control surfaces	inlet, nozzle/ afterbody, control surfaces	inlet, nozzle/ afterbody, control surfaces	control devices
Special problems	large Mach number span	propulsion integration, thermal management	propulsion integration, opposing design requirements	plasma effects

Without a quantification of features and effects we can say that for CAV-type and ARV-type vehicles viscosity effects play a large role. We call them viscosity-effects dominated vehicles.

RV-type vehicles are dominated by compressibility effects, with, as a consequence, large thermo-chemical effects. This holds also for the re-entry of an ARV-type vehicle and for AOTV-type vehicles.

Hence a CAV-type vehicle poses an aerothermodynamic (and multidisciplinary) design problem which is different from that of a RV-type vehicle. The CAV-type vehicle is drag sensitive, and must be, by necessity, slender, and flies at small angles of attack. The RV-type vehicle flies a “braking” mission. It must, therefore, have a blunt shape and flies at large angle of attack, which also helps to make surface radiation cooling very effective on such vehicles [1]. The reader is asked to study Table 2.1 in detail and to consider also the shapes and sizes of some RV-type and CAV-type flight vehicles shown in Fig. 2.1.

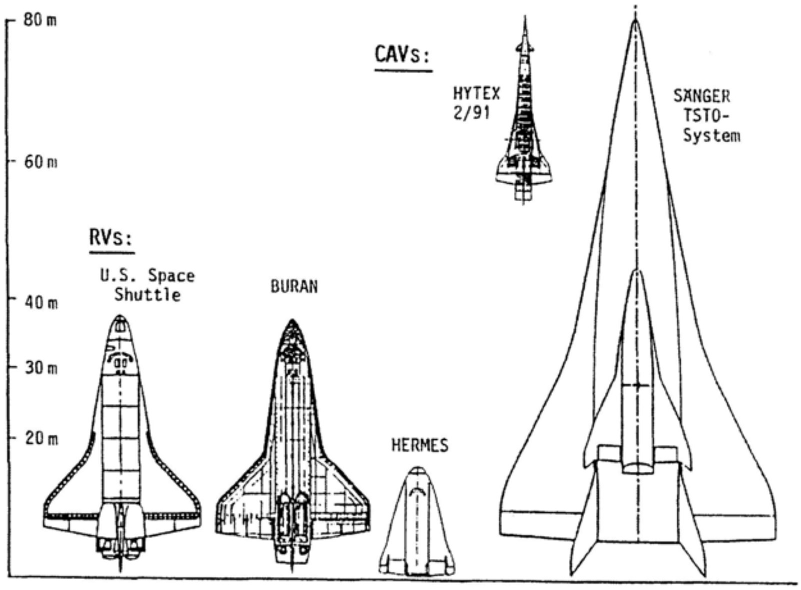

Fig. 2.1 Shape (planform) and size of selected RV-type and CAV-type flight vehicles [1]. HYTEX is an experimental vehicle studied in the German Hypersonics Technology Programme, [2].

It is pointed out further, Figs. 2.2 and 2.3, that due to the large angles of attack of RV-type flight vehicles down to approximately 30.0 km altitude, the flow and the thermo-chemical phenomena are concentrated on the windward side of the vehicle. This holds also for the mechanical and the thermal loads. The boundary layer on the windward side is, despite the high flight Mach numbers, a subsonic, transonic and at most low supersonic boundary layer [1].

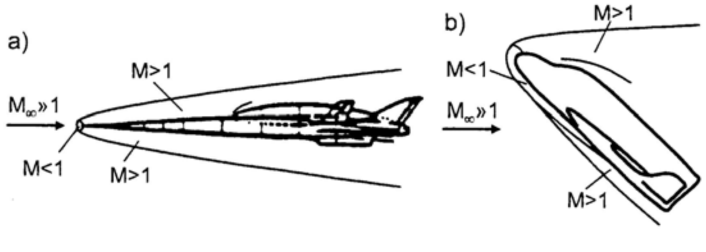

Fig. 2.2 Schematics of configurations of a) CAV-type and b) RV-type flight vehicles [1].

CAV-type flight vehicles fly aircraft-like at small angles of attack. The flow and the thermo-chemical (weaker than on RV-type vehicles) phenomena are similar on the lower (windward) and the upper (lee) side. This holds approximately, because the lower side may serve as the “first” ramp of the inlet system, also for the mechanical and thermal loads. The boundary layers are true hypersonic boundary layers, except for the small nose region [1].

Both RV-type and CAV-type flight vehicles employ surface radiation cooling. This leads to large temperature differentials on the windward and the lee side of RV-type vehicles, and smaller ones on CAV-type vehicles, Sub-Chapter 5.3. Of different size are also thermal surface effects [1], which concern predominantly thermo-chemical phenomena on RV-type vehicles, and viscous phenomena on CAV-type vehicles, Sub-Chapter 5.2.

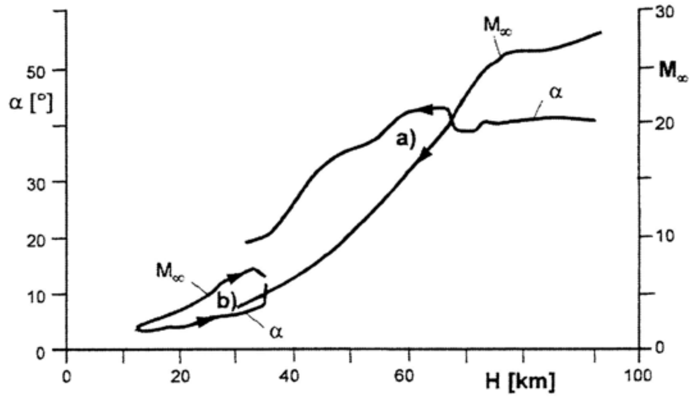

Fig. 2.3 Flight Mach number M_∞ and angle of attack α of a) the Space Shuttle, and b) the TSTO-system SÄNGER up to stage separation, as function of the flight altitude [1].

In closing this chapter, we note that only the Space Shuttle flies. BURAN flew once, and also several experimental vehicles, predominantly of RV-type, flew. Hence the actual design experience base is small and concerns only RV-type flight vehicles.

3. Air-Vehicle Engineering Issues

RV-type vehicles fly on their trajectories through the whole Mach number range from $M_\infty \approx 25$ down to landing speed. As a rule, they have cold primary structures and a thermal protection system (TPS). CAV-type vehicles fly at Mach numbers up to 7 to 12. They have always a highly integrated lift and propulsion system [5], the external (single expansion ramp) nozzle area is the larger the higher the flight Mach number is [6]. Such vehicles possibly will have hot primary structures. Anyway, cold primary structures with a tile-like TPS are ruled out, because the surfaces of these vehicles must be sufficiently smooth in order to avoid premature laminar-turbulent transition, and to avoid increments of viscous drag and of thermal loads, after the boundary layer has become turbulent [1].

The propulsion mode, propulsion cooling, the type of fuel and the material of the (hot primary) structure of a CAV-type flight vehicle hence are functions of the (largest) flight Mach number, Fig. 3.1 [7]. Although that figure dates back many years, and the location of the “technology jumps" may have shifted somewhat, it gives a good idea of the technology challenges connected to hypersonic flight with CAV-type flight vehicles.

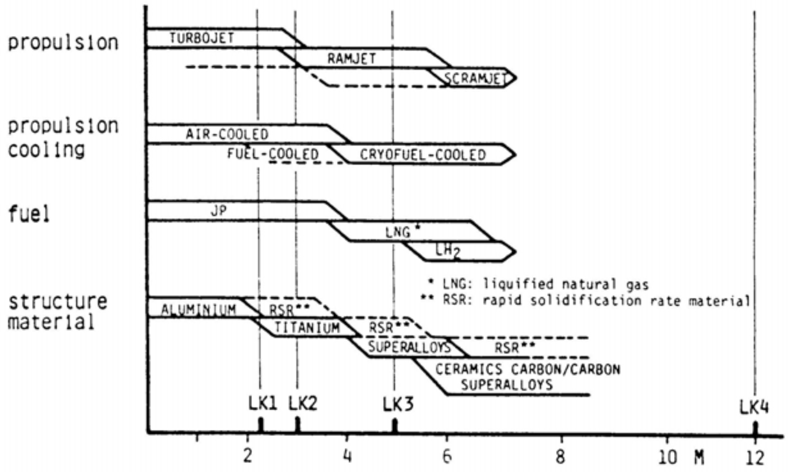

Fig. 3.1 Technology jumps with supersonic and hypersonic aircraft at rising flight Mach numbers, after [7]. LK1 to LK4 are reference concepts of a German study to define key technologies for high speed aircraft, see [5].

3.1 Requirements on Disciplines (Selection)

In this sub-chapter a short overview over the requirements on the disciplines involved in the design of hypersonic flight vehicles is given. It is based on the FESTIP Technology and Development Plan, [8], but lists only a selection of the topics discussed there.

- **Aerothermodynamics:** aerodynamic performance, flyability and controllability, propulsion/airframe integration (CAV-type vehicles), (upper) stage integration and separation for TSTO-systems, loads determination, surface properties determination, ...

- **Structures and materials:** structural topology, light-weight primary structures (RV-type vehicles: cold primary structure with TPS, CAV-type vehicles: (?) hot primary structure with internal insulation/integrated cryo-tank(s)), hot stabilisation and control surfaces, cryo-tank structures for CAV-type vehicles (integrated/non-integrated), TPS, materials, coatings, joints, seals, ...

- **Propulsion (rocket):** performance, weight, reusability, throttleability (landing engines), restartability, ...

- **Propulsion (airbreathing):** performance, weight, fuel consumption, propulsion/airframe integration with inlet, boundary-layer diverter, and nozzle, net thrust (thrust-vector changes with flight Mach number), cooling (inlet, core engine, nozzle, ...), ...

- **Subsystems:** flight mechanics/dynamics, flight control system, air-data system, general instrumentation, GNC, actuator systems, stage separation system for TSTO-systems, onboard power generation, ...

- **Thermal management:** passive (surface radiation) cooling, TPS, internal insulation, active cooling (internal, external), thermal household of CAV-type vehicles, ...

- **Reusability and operations:** health monitoring (airframe, TPS, engines), inspection, repair (airframe, TPS, engines), communications, abort capability, ground infrastructure, ground-support system, ...

- **All hardware disciplines:** manufacturability, maintainability, ...,

- **All process disciplines (aerothermodynamics, other disciplines partly):** use of information technologies and high-performance computation**.**

3.2 Some Special Issues of CAV-Type Flight Vehicles

In the above the major technical disciplines were listed separately. In reality strong couplings exist, for CAV-type flight vehicles to the degree, that Cayley's design paradigm [9] is completely annulled, Chapters 5 and 6. In the following two general examples of the synergy of aerodynamics, structures and propulsion in view of flight vehicle effectiveness are sketched.

- **Breguet's range equation:** This equation, written in the form

$$\frac{\text{burned fuel}}{\text{flight distance}} \sim \frac{\text{specific fuel consumption}}{M_\infty} \times \frac{\text{gross vehicle weight}}{L/D}$$

says that the amount of burned fuel per flight distance becomes the smaller, the smaller, on the one hand, the specific fuel consumption and the vehicle weight are, and on the other hand, the larger the flight Mach number M_∞ and the lift to drag (L/D) ratio are. The consequences for technology development and vehicle design are obvious.

- **Take-off mass sensitivity:**

Breguet's range equation can be used to study the sensibility of the flight vehicle's take-off mass as function of the ratio 'mass empty' to 'take-off mass'. In Fig. 3.2 an example is given from [10], with the lift to drag (L/D) ratio as parameter. The figure is schematic, but reflects a $M_\infty = 5$ CAV-type flight vehicle with a given mission [5]. In the original figure the specific impulse of the propulsion system is an additional parameter, which has been omitted here in order to make the figure better readable.

The (hypothetical) case A in Fig. 3.2 represents a design in which the take-off mass does not depend strongly on L/D: the design is not too sensitive. In the design process this would mean that a moderate design margin [11] regarding the aerodynamic performance can be taken.

The (hypothetical) case B in Fig. 3.2, however, represents a design in which the take-off mass depends strongly on L/D: the design is weight critical. The ratio 'mass empty' to 'take-off mass' in that case is realistic with regard to the present technology. Consequently, a good aerodynamic design with small uncertainties is necessary.

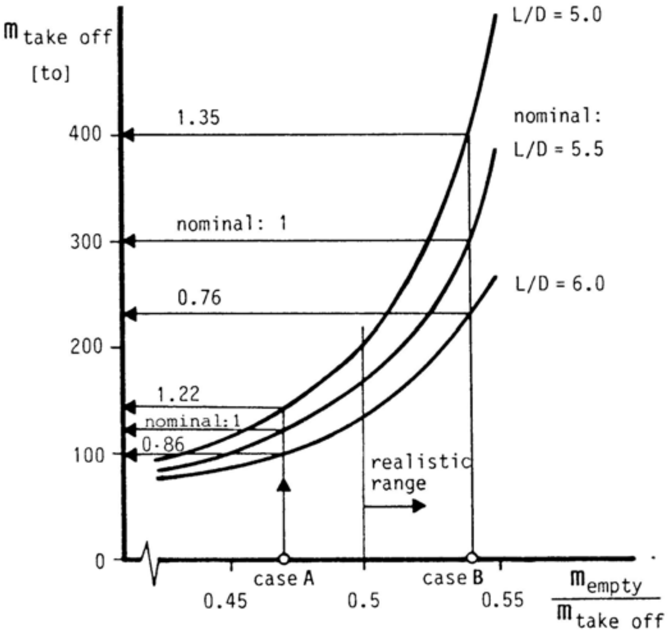

Fig. 3.2 Take-off mass sensitivity of a $M_\infty = 5$ CAV-type flight vehicle [10], [5].

These illustrations of the synergy of the three technical disciplines must be seen in view of the payload fraction (pay load/ dry mass empty), which, for instance, a TSTO space transportation system has. For the SÄNGER system this was estimated to be approximately 4.4 per cent [12] (rocket launcher: approximately 2 per cent), compared to that of an Airbus-like transport aircraft of 30 to 45 per cent. This means that the design margins are much smaller for hypersonic space transportation systems than for transonic aircraft. Hence the development risk is very much larger, which must be seen in the context of the also very much larger development costs, Chapter 6.

4. Major Programs and Flight Vehicles

In this chapter an overview is given, without attempting completeness, over major programs and flight vehicles by simply listing program and vehicle names, which are partly synonyms. Achievements and lessons learned are then sketched summarily. Since it is not possible in the frame of this paper to give a reference to each item, the reader is referred to [2] (unfortunately not yet available) and to [3].

4.1 RV-Type Flight Vehicles

- **USA:** X-20 (Dyna Soar), X-23/24, Space Shuttle, X-33, X-38 (crew rescue vehicle), Orbital Space Plane (OSP) ?.

- **Europe:** HERMES/MAIA, EARL, reusable rocket launcher (RRL/RRLD), ESA Winged Launcher Concepts (WLC), FESTIP (several vehicle concepts including experimental/

demonstrator vehicles (EXTV)), ESA Future Launcher Preparatory Program (FLPP) including experimental vehicle concepts.

- **Russia:** BOR, BURAN, MAKS, ORYOL (several vehicle concepts).

- **Japan:** HYFLEX, HOPE-X, HOPE.

Achievements and Lessons Learned

Regarding the achievements and lessons learned, the major ones from the Space Shuttle [13], [14] are listed and then summarily general results of all programs and vehicles.

- **Space Shuttle:** RV-type flight vehicles of that kind are feasible! The vehicle showed more or less the expected performance. Major problems were the pitching-moment anomaly, the over-dimensioning of the TPS, and unexpected high thermal loads at the OMS pod. The expected substantial reduction of specific transportation cost was not achieved. The major reason are the very costly and time consuming ground operations to inspect, maintain and repair the vehicle after flight, and to prepare it for the new flight. The large number of tiles of the TPS, O(30,000), is a special problem. Advanced TPS technologies, but also possibly other shapes of the lower side of the re-entry vehicle (without adverse effects regarding the aerodynamic properties) are needed. Ground operations are a topic which needs special attention when designing and developing new space transportation systems, [8], but also general hypersonic aircraft.

- **General results of all programs and vehicles so far:** Experience was and is gained in the design, manufacturing and operation of RV-type flight vehicles. TPS materials and technologies were developed, also general design and testing methods and tools. The methods of numerical aerodynamics/aerothermodynamics were evolved, also as problem diagnosis tools [11], for instance regarding the Space Shuttle pitching-moment anomaly. GNC for RV-type vehicle flight was advanced, BURAN and HYFLEX flew fully automatically. Systems engineering of the flight vehicles followed the lines of aircraft development.

4.2 CAV-Type Flight Vehicles Including Airbreathing Propulsion Systems

Because the boundaries between CAV-type and ARV-type flight vehicles are partly somewhat fluent, programs and vehicles of both type are listed.

- **Early German:** Orbital bomber or “atmosphere skipper” by E. Sänger and I. Bredt. Start with a rocket sled, then rocket propulsion. Project in the first half of the 1940ties. In the second half of the 1940ties taken up again in the USSR with two ram engines at the wing tips (M. W. Keldish).

- **USA:** X-15 (rocket propulsion), NASP/X-30 (National Aerospace Plane), X-43, OSP (?).

- **Europe:** Junkers Space Transporter RT8 (TSTO concept by E. Sänger), HOTOL, STS 2000/STAR-H, SÄNGER II, German HTP, WLC concepts, PREPHA, FESTIP (several vehicle concepts), FLPP.

- **Russia:** ORYOL (several vehicle concepts).
- **Japan:** Space Plane.

Achievements and Lessons Learned

- **Flight experience:** Except for flight tests of propulsion systems, e. g. X-34, no real flight vehicle and no flight.
- **General results of all programs so far:** Ram/scram propulsion concepts and technologies were advanced up to ground tests and a few flight tests. Vehicle concepts and technologies were evolved, including materials and structures (hot structures), cryo tank technologies, et cetera. Insight was gained with regard to multidisciplinary design and engineering problems, concerning, for example, the multidisciplinary implications of surface radiation cooling (structures and materials ↔ aerothermodynamics), and also the problem of propulsion/airframe integration. Potentials and deficits of ground-simulation facilities, the role of flight tests, the transfer model ansatz, et cetera, were identified.

5. Selected Design and Development Issues from HERMES and SÄNGER Work

With the following short considerations, some topics and general results from the HERMES project and from the German Hypersonics (SÄNGER) Technology Programme are presented.

5.1 HERMES Shape Definition and the Need for Experimental Vehicles

The aerodynamic shape definition of HERMES was characterised by a very risk-conscious approach. The basic configuration was radically different from that of the Space Shuttle (and BURAN), Fig. 2.1, the configurational experience gained with that flight vehicle hence could not be used. The basic differences of the configurations were due to the different launch approaches [15]. Further had the Shuttle's pitching-moment anomaly shown, that the Mach number independence principle of Oswatitsch, see, e. g., [1], had certain restrictions. It is this principle which permits an effective aerodynamic ground-facility simulation for hypersonic flight vehicle design.

During the shape definition of HERMES a large variety of configuration changes around the compact basis configuration, [16], was performed. Consequently the methods of numerical aerothermodynamics, which at that time were still risky to apply, were used in the shape definition process. Besides the Dassault company, which was responsible for the aerodynamic design, several "alternate" European companies and research establishments applied their numerical methods, which were different from those of Dassault, to key design issues (dissimilar approaches).

The numerical methods needed improvement and validation. Therefore early on a downscaled HERMES configuration, MAIA, was considered as an experimental vehicle. The main objectives of MAIA were, [17], to acquire, in real flight, aerothermodynamic data for a better understanding of phenomena, for an improvement of thermodynamic models, et cetera, all with the ultimate goal to establish and validate the methods of numerical aerothermodynamics as "phenomena-oriented" design tools. An overarching objective was to gain systems and flight experience with an experimental vehicle, in order to reach European autonomy in re-entry technologies.

The HERMES and MAIA work has yielded much insight and experience (in view of the downscaling of the original HERMES configuration to the MAIA configuration also concerning the implications of surface radiation cooling, Sub-Chapter 5.2). Considering the world-wide still rather small design experience regarding winged re-entry vehicles, it is very advisable to pursue RV-type experimental vehicles further [18].

5.2 General Implications of Surface Radiation Cooling

Surface radiation cooling is the major (passive) cooling means for outer surfaces of RV-type, CAV-type and ARV-type flight vehicles. It was for a long time a topic only for the structures and materials discipline. Some issues of it are discussed here because it concerns aerothermodynamics, too, especially with regard to CAV-type and ARV-type flight vehicles.

Three heat fluxes and the wall temperature T_w define the thermal state of a radiation-cooled surface, Fig. 5.1, [1]. The radiation-adiabatic wall temperature T_{ra} is given, if $q_w = 0$.

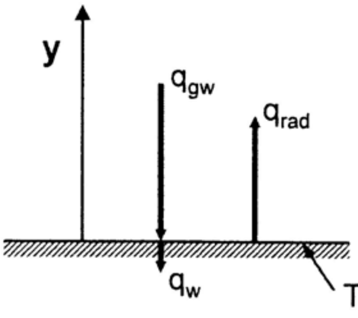

Fig. 5.1 Schematic of the local heat fluxes at a radiation-cooled surface [1]: q_{gw} is the heat flux in the gas at the wall, q_{rad} is the surface radiation heat flux, and q_w the (small) heat flux into or out of the wall.

The thermal state of the surface is given by the wall temperature T_w and by the temperature gradient in the gas at the wall normal to it, $\partial T/\partial n|_{gas,wall}$ or, with perfect/equilibrium gas, q_{gw}. It governs both thermal surface effects (viscous and thermo-chemical) and thermal loads, Fig. 5.2, which should be distinguished. The thermal state of the surface is governed by the general flow parameters, but also by the surface properties. A large surface emissivity is necessary, surface roughness et cetera, also surface catalycity, should be sub-critical [1].

The most important topics of the influence of the thermal state of the surface on aerothermodynamic wall and near-wall phenomena and on structure and materials issues are listed in Table 5.1. A detailed discussion is not possible in the frame of this paper. In any case it should be observed, that both the wall temperature and one heat flux, partly together, partly alone, govern thermal surface effects and thermal loads at the vehicle surface, and hence aerodynamic forces and properties, and several structure and materials issues [1].

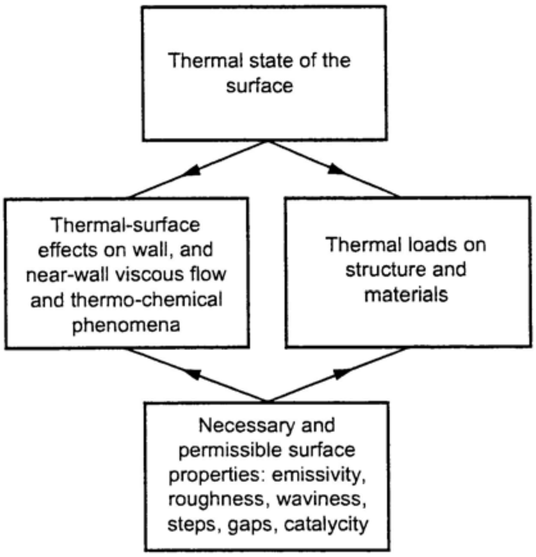

Fig. 5.2 The thermal state of the surface and its different design implications [1].

Table 5.1 Wall and near-wall viscous-flow/ thermo-chemical phenomena, and structure and materials issues influenced by the thermal state of the surface [1]. ( ) indicates indirect influence, the basic M, Re, et cetera dependence is not indicated.

Item	T_w	$\partial T/\partial n\|_{gw}$	$\partial T/\partial n\|_w$
Boundary-layer thicknesses(δ, δ_1, ...)	X		
Skin friction	X		
Heat flux in the gas at the wall q_{gw}	X	X	
Surface-radiation heat flux q_r	X	(X)	(X)
Laminar-turbulent transition	X	X	
Turbulence	?	?	
Controlled and uncontrolled flow separation	X		
Shock/bondary-layer interaction	X		
Hypersonic viscous interaction	X		
Catalytic surface recombination	X	(X)	
Transport properties at and near the surface	X	X	
Heat flux into the wall q_w	X	(X)	X
Material strength and endurance	X		
Thickness of TPS or internal insulation (time integral of q_w)	X		X

5.3 Example of Thermal Surface Effects: Wall Temperature and Skin Friction

Fig. 5.3 shows the wall temperature on the lower and partly also on the upper symmetry line of the forebody of the lower stage of SÄNGER computed with different assumptions regarding the state of the boundary layer (laminar/turbulent), gas model and radiation cooling [1].

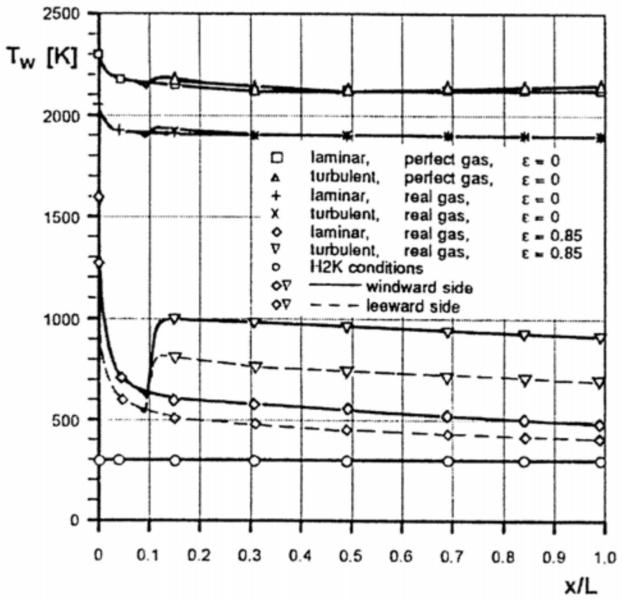

Fig. 5.3 Wall temperatures on the lower and the upper symmetry line of the forebody of the lower stage of SÄNGER in the flight and in a wind tunnel situation [19], [20], [1] (configuration see Fig. 5.4). Influence of the state of the boundary layer, the gas model, and radiation cooling. $M_\infty = 6.8$, H = 33.0 km, $\alpha = 6^\circ$, Navier-Stokes solution.

For the case without radiation cooling, emissivity ε = 0, perfect gas, the wall temperature (recovery temperature) is not much affected by the state of the boundary layer (laminar-turbulent transition was enforced at x/L = 0.1). The assumption of equilibrium real gas lowers the temperature by approximately 300.0 K. If radiation cooling is switched on, ε = 0.85, the situation changes drastically. The wall temperature, now the radiation-adiabatic temperature, which depends on both the Mach number and the Reynolds number, drops very fast by approximately 1,400.0 to 1,600.0 K. Laminar-turbulent transition has a very strong effect by rising the temperature again by about 400.0 K. The temperature on the upper side of the forebody is lower by 80.0 K (laminar flow) and 200.0 K (turbulent flow).

Different wall temperatures lead to different skin friction [1]. This is shown for the lower side of the forebody, Fig. 5.4. If the flow is laminar, the skin friction is not much affected by the wall temperature, curve at the bottom of the figure. This is different if the flow is turbulent. The skin friction for the radiation-cooled case is about 30 per cent larger than for the adiabatic case, and much larger for the cold surface (300.0 K) of the wind tunnel model.

Important is the observation, that for turbulent flow a higher wall temperature reduces skin friction. Hence the surface of a CAV-type flight vehicle should be flown as hot as possible. This could be achieved by a tailoring of the surface emissivity – a challenge for the coating technology – such that materials limits are approached as far as possible. This is an optimisation problem, since this could also mean, that more sophisticate materials and coatings are to be employed.

It is finally noted, that the wall temperature also affects the boundary-layer thickness (important for the height of the boundary-layer diverter ahead of the inlet, and for the effectiveness of control surfaces), however stronger for laminar than for turbulent flow.

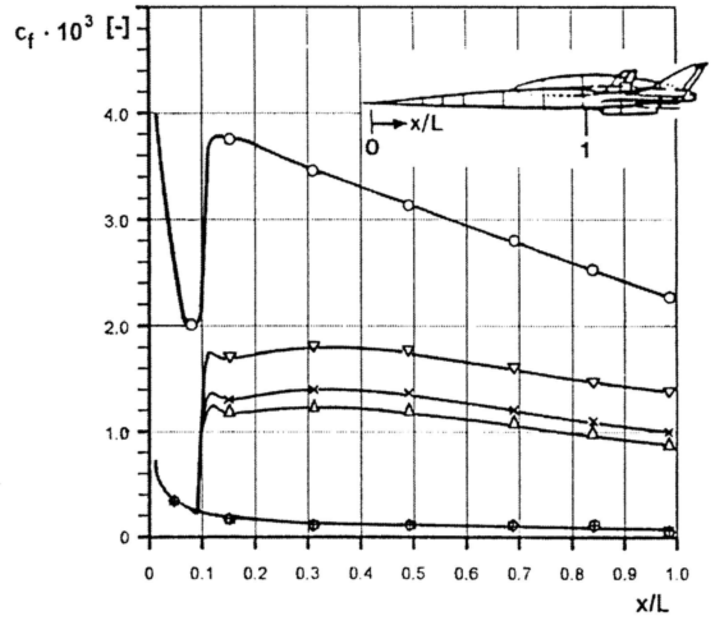

Fig. 5.4 Skin friction on the lower symmetry line of the forebody of the lower stage of SÄNGER in the flight and in a wind tunnel situation [19], [20], [1]. Influence of the state of the boundary layer, the gas model, and radiation cooling. Flight parameters and symbols see Fig. 5.3.

The viscous drag in the above example is about 30 per cent of the total vehicle drag. Since the result is representative for CAV-type flight vehicles, the simulation problem is obvious. It is not possible to simulate these effects in ground facilities [1]. The computational simulation on the other hand is strongly hampered, because transition criteria of sufficient accuracy and reliability are not available [1]. How good the available turbulence models are, is not clear, however, the problem of turbulence modelling seems not to be so severe, if the flow is attached.

An example for a viscous effects sensitive, especially transition sensitive flight vehicle was NASP/X-30 [21]. The uncertainty of the location of laminar-turbulent transition affected the take-off mass by a factor of two and more. Influenced by a large, although different degree, were seen to be the thermal loads, viscous drag, and the inlet-onset flow (height of the boundary-layer diverter). If the vehicle had anyway a large ‘mass empty’ to ‘take-off mass’ ratio, Fig. 3.2, this result is understandable.

5.4 Propulsion/Airframe Integration and “Thrust minus Drag”

The lower side of a CAV-type vehicle is an integrated lift and propulsion system. Propulsion/airframe integration is influenced by many aerothermodynamic phenomena, Fig. 5.5.

The external flow path on the lower side of the forebody is characterised by the boundary-layer development, which itself is influenced by a number of factors, first of all the transition location. A large role plays the forebody pre-compression, Sub-Chapter 5.5. In this context also the aero-thermoelasticity of the airframe is of importance, especially if a hot primary structure is envisaged. The fact, that large portions of the surface are radiation cooled, leads to temperature differentials between the lower and the upper side of the vehicle (depending on the flight Mach number it might be necessary to actively cool the vehicle nose region, if for wave-drag reasons the nose diameter is too small for an effective radiation cooling). The external flow path behind the propulsion unit is characterised by the nozzle/afterbody flow. The larger the flight Mach number, the larger is the surface of the external nozzle [6].

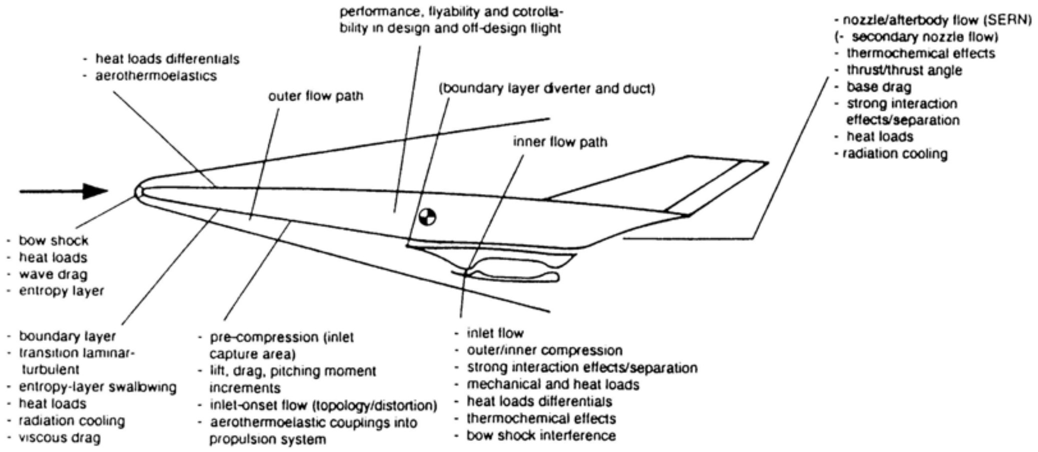

Fig. 5.5 Major topics and issues of aerothermodynamic propulsion/airframe integration [22].

All the aerothermodynamic phenomena in the external flow path, but also the aeroelastic behaviour of the air frame, the internal (engine) flow path, including the flow through the boundary-layer diverter duct (necessary for the turbo mode, most probably also for the ram and the scram mode), are relevant for the magnitude and the direction of the net thrust, Fig. 5.6.

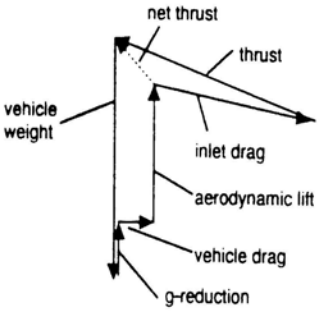

Fig. 5.6 Point-force polygon (schematically) of a CAV-type flight vehicle (stationary flight) [5].

The net thrust is the (small) difference between several large forces which depend on flight speed, altitude, angle of attack, pre-compression, the external and the internal flow path, and the engine setting. Besides the problem to arrive at a positive “thrust minus drag”, sufficient lift must be created, and it must be possible to trim and to control the vehicle. These issues are very critical too, because the direction of the thrust vector changes with the flight Mach number, which is a drawback of the expansion-ramp nozzle (bell nozzles are not appropriate for CAV-type flight vehicles).

5.5 Forebody Pre-Compression and Aero-Thermoelastic Deformation

The lower side of the forebody of an airbreathing CAV-type flight vehicle is flat in order to achieve a two-dimensional inlet-onset flow (conical shapes have been proposed and studied, too).

If the lower side is inclined against the flight direction by a small angle, the resulting "pre-compression" can lead to a substantial reduction of the inlet capture area. Of course this goes along with an increase of the lift, but also of the drag, and a change of the aerodynamic pitching moment. Trade-offs must help to determine the optimum degree of pre-compression.

During the (pre-) design of the lower stage of SÄNGER an effective inclination of the lower side of approximately 9° resulted, for $M_\infty = 6.8$, in a reduction of the capture area of approximately 50 per cent [12]. This, however, was bought with a problematic angle of attack sensitivity of the net thrust, Fig. 5.7.

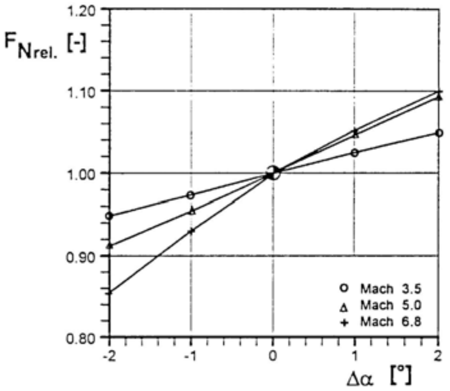

Fig. 5.7 Influence of (effective) angle of attack changes of the lower side of the SÄNGER forebody on the net installed thrust [23], [12].

At $M_\infty = 6.8$ only one degree less than the nominal angle of attack reduces the net thrust by approximately 7 per cent. One degree more gives about five per cent more thrust. Of course, drag, lift and pitching moment will be changed, too, what was not taken into account in [23]. In any case, the indicated sensitivity to such minute changes of the effective angle of attack of the lower side of the forebody would pose a very large vehicle, inlet and engine control problem, which would be enhanced by the static and dynamic aero-thermoelasticity of the forebody.

The forebody aero-thermoelasticity poses a particular problem, because with the present airframe design and development approaches, its modes and their magnitudes will become available with the needed accuracy only very late in the development process, Chapter 6.

The possible static aero-thermoelastic deformation of the SÄNGER forebody is illustrated in Fig. 5.8. A hot primary structure was assumed with such a structural design, that the heating of the structure results in a deformation rather than in additional stresses [24]. At the flight condition considered ($M_\infty = 6.8$, $H = 31.0$ km, $\alpha = 6°$, turbulent flow), the nominal radiation-adiabatic temperature on the upper side is approximately 200.0 K lower than on the lower side, Fig. 5.3. This leads to an effective primary upward "bananisation", [24], of the forebody by approximately 2.0 m, Fig. 5.8. The figure shows also the influence of other factors.

A proper insulation [24], better a tailoring (increase) of the surface emissivity on the upper side, which as side effect would reduce the turbulent skin friction, Sub-Chapter 5.3, would omit the effect to a large degree. In view of the dynamic aeroelasticity of the forebody and the thrust sensitivity, a (stiffer ?) cold primary structure with a TPS could be an interesting alternative to the hot primary structure. The TPS, however, must have a sufficiently smooth surface in order to avoid increments of skin-friction and thermal loads [1].

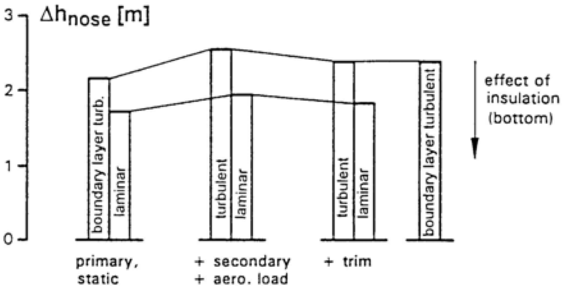

Fig. 5.8 Idealised effect of the temperature difference between the lower and the upper side of the forebody (L = 55.0 m) of the SÄNGER lower stage on its static aeroelastic behaviour [24], [12], Δh_{nose} is the nose-up displacement.

5.6 Most Critical Challenges in CAV-Type Flight Vehicle Design and Development

The challenges sketched here hold for large CAV-type vehicles, for instance for the lower stages of space-transportation systems [12]. Small vehicles, for instance airbreathing experimental vehicles, are only partly concerned.

The most critical design and development challenges identified in the German Hypersonics Technology Programme for the SÄNGER lower stage are [12]:

- The determination and verification of the viscous drag of the lower stage, the viscous (boundary layer) inlet-onset flow, and the thermal loads in view of the thermal surface effects and the principal deficits of ground-facility simulation, and the deficits of flow-physics models in computational simulation methods, notably laminar-turbulent transition criteria.

- The ground-facility verification of a (hot) ram/scram propulsion inlet in a realistic environment.

- The ground-facility verification (free-jet test) of a ram/scram propulsion system (inlet, core engine, nozzle) under real flight conditions (one propulsion unit of the lower stage of SÄNGER has approximately 2.0 m diameter and 30.0 m length).

- The static and the dynamic ground-facility test and verification of a large hot primary structure (SÄNGER lower stage: 80.0 m length, $T_{structure} \approx$ 1,000.0 K). The consequences, that such tests would happen anyway very late in the development process will be considered in the next chapter.

6. Making Use of the Second Mathematisation Wave

The discussion in the preceding chapters has shown, that a considerable technology bases has been achieved world-wide so far, and that also many partly very serious technology challenges have been identified. This picture is different for the different flight vehicles classes considered, with the airbreathing vehicles of CAV- and ARV-type being most critical.

No future single extraordinary break-through can be expected in one of the involved disciplines of hypersonic flight vehicle design, development and manufacturing, which would make things suddenly easy and feasible.

The overall picture, very simplified, can be sketched as follows:

- Rocket propulsion sees a saturation (?) of the specific impulse, but still very many requirements, Sub-Chapter 3.1, have to be fulfilled.

- Airbreathing propulsion shows a large future potential, many requirements are still to be fulfilled, Sub-Chapter 3.1. As a very large challenge is seen the effective propulsion/airframe integration for a large-scale flight vehicle.

- Structures and materials also have to fulfil many requirements, a saturation (?) is seen regarding the specific weight of materials.

- Multidisciplinary simulation, design and optimisation, with numerical aerothermodynamics being the key discipline, has a very large potential to help in making future hypersonic flight vehicles/systems feasible and efficient.

The design and development of hypersonic flight vehicles takes a long time and needs huge amounts of funding. As was discussed and shown in Chapter 3 and in Sub-Chapter 4.1, also the issues of operation and reusability must be regarded, with repercussions on the flight vehicle and its propulsion system. For CAV-type flight vehicles all must be seen in view of the large take-off mass sensitivity of these vehicles and their small pay-load fraction, Sub-Chapter 3.2. All this together introduces large program risks. The efforts to create a CAV-type flight vehicle, and the involved risks are certainly larger for this class of vehicles than for RV-type vehicles. They are largest for airbreathing ARV-type vehicles which have several opposing design requirements, Table 2.1.

Regarding RV-type vehicles the experience made with the Space Shuttle, and the results of subsequent technology work, suggest that not only the involved disciplines must evolve their technology bases further, but that also for them true multidisciplinary design and optimisation has a very large potential, which must be realised in future. This concerns especially the determination of thermal and mechanical loads, but also the aerodynamic shape definition process. The challenges to arrive at this goal are manifold and large [9], [11].

For CAV-type flight vehicles Cayley’s design paradigm (de-coupling of subsystems and their functions, de-coupling of the involved disciplines [9], [11]) is almost completely annulled. The lower side of such vehicles is a fully integrated lift and propulsion system, with large consequences also for the operation (flight mechanics/dynamics) of the vehicle.

An important issue for both RV-type and CAV-type flight vehicles, but especially for the latter, is that with the present flight vehicle development approach the actual quantification of the aero-thermo-servoelastic properties of the vehicle’s airframe is made only very late in the development process, [11], after the first - already completely defined and developed - airframe has been assembled. Partly this quantification process extends deep into the flight envelope opening process. Changes - actually “repair solutions” - which must be made of the airframe, if the said properties don’t meet the requirements, are very costly and usually will increase structural weight.

Looking at the take-off mass sensitivity and the small pay-loads of RV- and CAV-type flight vehicles, at the net-thrust sensitivity of CAV-type flight vehicles discussed in Sub-Chapter 5.5, at the large airframe of CAV-type vehicles in general, and in view of the presently on-going discussion of possible unstable flight of RV-type vehicles, which certainly will be extended to CAV-type vehicles, too, the above discussed late determination of the aero-thermo-servo-elastic properties of the airframe can turn out to be a true show stopper, if no counter measures are taken.

The aero-thermo-servoelasticity problem concerns predominantly CAV-type flight vehicles. To cope with it, the transfer model concept, [12], was developed in the frame of the German Hypersonics Technology Programme for the lower stage of SÄNGER. This concept, which in generalised form is of interest for all kinds of design and development issues of flight vehicles, makes use of the second mathematisation wave in sciences and engineering [9]. At the core of it is the virtual product, [9], which is defined as the “high-fidelity mathematical/nu-merical representation of the physical properties and the functions of a product”.

The virtual product ansatz - a concept in discussion for classical aircraft design and development - should permit to reduce design and development risks and costs by a highly integrated system definition and development approach, which is necessary due to the waning (also in classical aircraft development) of Cayley’s design paradigm, by an improved system layout with a much more accurate and reliable loads determination than possible today, and by the overcoming of the gap between product definition and development regarding the static and dynamic aero-servoelastic properties of the airframe.

The virtual product approach would lead to a change of the role of ground-facility simulation, and would put more emphasis on disciplinary and true multidisciplinary numerical simulation and optimisation methods. Systems engineering and the sequence of the design phases, as it exists today [11], would have to be changed, too, Fig. 6.1.

That such an approach is imaginable at all - there is no doubt about its necessity - is due to still enormous growth of computer power and the capabilities of information technologies [9]. The methods of numerical aerodynamics are key methods in such an approach. Large advancements, however, are necessary in flow-physics modelling (laminar-turbulent transition, turbulence, turbulent separation). Large advancements - and a new thinking - are necessary, too, in structure mechanics. Structure-physics models are necessary in order to permit to quantify the influence of joints of all kind, of non-linear deformations, et cetera, if static and dynamic aeroelastic properties of the airframe are to be described and optimized with high accuracy and reliability not late in the development process in a ground-simulation facility, but much earlier.

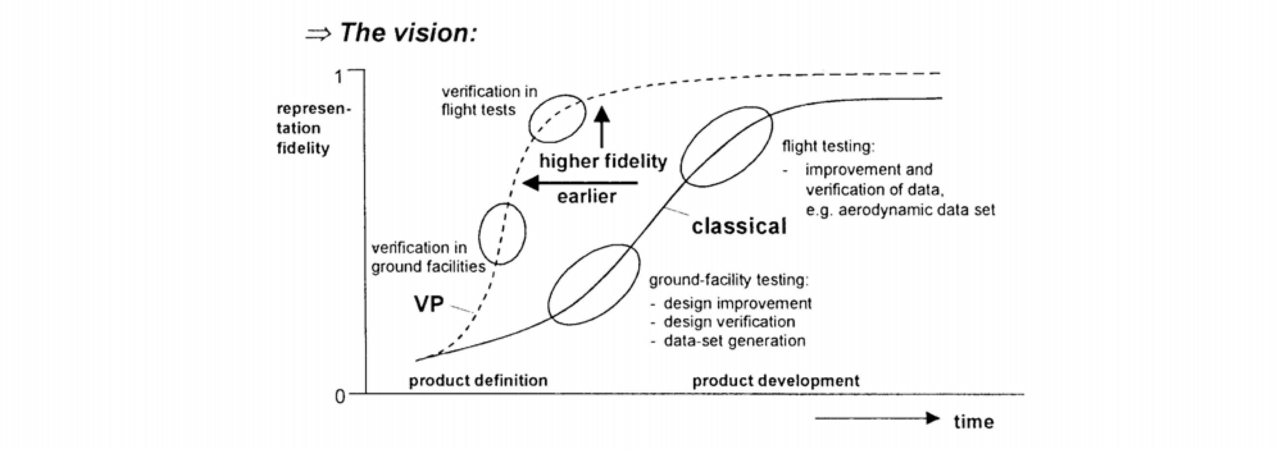

Fig. 6.1 Schematic of the potential of the virtual product approach [9].

It is clear that the virtual product approach is a topic too for the design and development of hypersonic flight vehicles. Here the situation is much more critical than in classical aircraft design due to the large sensitivities and the small pay-load fraction, Sub-Chapter 3.2, on the one hand, and due to the deficiencies - which are partially principle deficiencies, which cannot be overcome - of ground-facility simulation.

The transfer model approach, [12], takes especially also the latter issue into account. A simulation triangle with a systematic combination of computational simulation, ground-facility simulation, and in-flight simulation with a succession of dedicated experimental vehicles (to gain insights into phenomena and engineering issues, to obtain data for modelling issues, to check and validate the transfer model approach itself, et cetera), is at the centre of the approach. The transfer model approach will permit for both RV-type and CAV-type flight vehicles, although with different points of main effort, the step-wise opening of the technology envelope and the flight envelope. Of course, one has to spend more money initially, but with the benefit of an effective reduction of the design risks and costs of the final flight system.

Cost and time to develop new hypersonic flight and transport systems are so big, that a large design problem or a failure, which shows up in the development process, will kill the program. This happened already several times. Therefore an effective technology preparation is necessary, which, of course, needs continuous work and funding over many years, maybe even decades. The transfer model approach is an approach concerning air-vehicle layout and engineering of new hypersonic flight systems, the technological challenges in propulsion, structure and materials et cetera remain to be of huge size and importance.

7. Conclusion

It was shown that the technology development for hypersonic flight is an on-going process since several decades. Much and important system and technology knowledge has been gained, although only one flight vehicle, the Space Shuttle, became operational so far. Long and continuous effort is still needed to arrive at more efficient space-transportation systems and at (possible) hypersonic aircraft. Re-entry (RV) type flight vehicles pose design challenges, which are different from those of airbreathing cruise and acceleration (CAV) type vehicles, however, both vehicle types are mass sensitive and have very small pay-load fractions. CAV-type flight vehicles will make use of ram/scram propulsion, which has a large potential, but needs still long time to become operational. The problem of propulsion/airframe integration poses engineering challenges, which have not yet been understood in all their details and consequences.

Regarding air-vehicle engineering, the second mathematisation wave in sciences and engineering must be put to use also for hypersonic flight vehicle design and development. The virtual product and the transfer model approach are systematic ansatzes in this regard. The basics for the mathematical/numerical modelling of aerothermodynamics, propulsion, structures and materials must be improved. Experimental vehicles are needed to gain data for the development of such ansatzes, to check and validate them, and to open the technology envelope and the flight envelope of both RV- and CAV-type flight vehicles.

8. References

[1] E. H. Hirschel: "Basics of Aerothermodynamics". Springer-Verlag, Berlin/Heidelberg/ New York, and Volume 206 of Progress in Astronautics and Aeronautics, AIAA Inc., Washington, D. C., 2004.

[2] H. Kuczera, P. W. Sacher: "Reusable Space Transportation Systems". Springer-Verlag, Berlin/Heidelberg/ New York and Praxis Publishing, Chichester, 2005.

[3] J. Miller: "The X-Planes X-1 to X-45". Midland Publishing, U. K., 3rd edition, 2001.

[4] D. M. Bushnell: "Hypersonic Ground Test Requirements". *F. K. Lu, D. E. Marren (eds.), Advanced Hypersonic Test Facilities*. AIAA, Washington, D. C., 2002, pp. 1 - 15.

[5] E. H. Hirschel: "Aerothermodynamic Phenomena and the Design of Atmospheric Hypersonic Airplanes". *J. J. Bertin, J. Periaux, J. Ballmann (eds.), Advances in Hypersonics, Vol. 1, Defining the Hypersonic Environment*. Birkhäuser, Boston, 1992, pp. 1 – 39.

[6] C. L. W. Edwards, W. J. Small, J. P. Weidner: "Studies of Scramjet/Airframe Integration Techniques for Hypersonic Aircraft". AIAA-Paper 75-58, 1975.

[7] N. N.: "Aeronautical Technology 2000, a Projection of Advanced Vehicle Concepts". National Academic Press, USA, N86-13235, 1985.

[8] E. H. Hirschel, F. G. J. Kremer: "Technology Development and Verification Plan – Overall Logics and Programmatics". Daimler-Benz Aerospace, Space-Infrastructure, FESTIP FSS-SCT-RP-0038, 1997.

[9] E. H. Hirschel: "Towards the Virtual Product in Aircraft Design?". *J. Periaux, M. Champion, J.-J. Gagnepain, O. Pironneau, B. Stoufflet, P. Thomas (eds.), Fluid Dynamics and Aeronautics New Challenges*. CIMNE Handbooks on Theory and Engineering Applications of Computational Methods, Barcelona, Spain, 2003, pp. 453 - 464.

[10] H. Lifka: "Aerodynamische und leistungsparametrische Analyse von Transportflugzeugen im $M_\infty = 5$ Bereich im Rahmen der BMFT-Studie "Überschallflugzeuge" für Konzept 3". MBB/LKE121/HY-PAC/R/003/A, 1987.

[11] J. B. Vos, A. Rizzi, D. Darracq, E. H. Hirschel: “Navier-Stokes Solvers in European Aircraft Design”. Progress in Aerospace Sciences, Vol. 38, 2002, pp. 601 - 697.

[12] E. H. Hirschel: “The Technology Development and Verification Concept of the German Hypersonics Technology Programme”. AGARD R-813, 1996, pp. 12-1 to 12-15.

[13] J. P. Arrington, J. J. Jones (eds.): “Shuttle Performance: Lessons Learned”. NASA CP-2283, 1983.

[14] D. A. Throckmorton (ed.): “Shuttle Performance: Lessons Learned”. NASA CP-3248, 1995.

[15] M. Trella: “Introduction to the Hypersonic Phenomena of HERMES”. *J. J. Bertin, R. Glowinski, J. Periaux (eds.), Hypersonics, Vol. 1, Defining the Hypersonic Environment*. Birkhäuser, Boston, 1989, pp. 67 – 91.

[16] P. Perrier: “Concepts of Hypersonic Aircraft”. *J. J. Bertin, J. Periaux, J. Ballmann (eds.), Advances in Hypersonics, Vol. 1, Defining the Hypersonic Environment*. Birkhäuser, Boston, 1992, pp. 40 – 71.

[17] E. H. Hirschel, H. Grallert, J. Lafon, M. Rapuc: “Acquisition of an Aerothermodynamic Data Base by Means of a Winged Experimental Vehicle”. Z. Flugwissenschaften und Weltraumforschung (ZFW), Vol. 16, 1992, pp. 15 - 27.

[18] M. Caporicci, L. Basile: “ESA Activities on Atmospheric Re-Entry Systems”. AIAA-Paper 2003-7017, 2003.

[19] M. A. Schmatz, R. K. Höld, F. Monnoyer, Ch. Mundt, H. Rieger, K. M. Wanie: “Numerical Methods for Aerodynamic Design II”. Space Course Aachen 1991, RWTH Aachen, 1991, pp. 62-1 to 62-40.

[20] R. Radespiel, personal communication, 1994.

[21] J. F. Shea: “Report of the Defense Science Board Task Force on the National Aerospace Plane (NASP)”. Office of the Under Secretary of Defense for Acquisition, Washington, D. C. 1988.

[22] E. H. Hirschel: “Aerothermodynamics and Propulsion Integration: Synthesis of the AGARD-FDP-VKI Special Course, April 15 – 19, 1996”. AGARD-CP-600, Vol. 3, 1997, pp. C34-1 to C34-8.

[23] A. Schaber: “Einfluss entscheidender Triebwerksparameter auf das Leistungsverhalten eines Hyperschall-Antriebs”. MTU-N94-EP-0001.

[24] W. Staudacher, J. Wimbauer: “Design Sensitivities of Airbreathing Hypersonic Vehicles”. AIAA-Paper 93-5099, 1993.