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Basics of Aerothermodynamics

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With 147 Figures

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Preface

The last two decades have brought two important developments for aerothermodynamics. One is that airbreathing hypersonic flight became the topic of technology programmes and extended system studies. The other is the emergence and maturing of the discrete numerical methods of aerodynamics/aerothermodynamics complementary to the ground-simulation facilities, with the parallel enormous growth of computer power.

Airbreathing hypersonic flight vehicles are, in contrast to aeroassisted re-entry vehicles, drag sensitive. They have, further, highly integrated lift and propulsion systems. This means that viscous effects, like boundary-layer development, laminar-turbulent transition, to a certain degree also strong interaction phenomena, are much more important for such vehicles than for re-entry vehicles. This holds also for the thermal state of the surface and thermal surface effects, concerning viscous and thermo-chemical phenomena (more important for re-entry vehicles) at and near the wall.

The discrete numerical methods of aerodynamics/aerothermodynamics permit now - what was twenty years ago not imaginable - the simulation of high speed flows past real flight vehicle configurations with thermo-chemical and viscous effects, the description of the latter being still handicapped by insufficient flow-physics models. The benefits of numerical simulation for flight vehicle design are enormous: much improved aerodynamic shape definition and optimization, provision of accurate and reliable aerodynamic data, and highly accurate determination of thermal and mechanical loads. Truly multidisciplinary design and optimization methods regarding the layout of thermal protection systems, all kinds of aero-servoelasticity problems of the airframe, et cetera, begin now to emerge.

In this book the basics of aerothermodynamics are treated, while trying to take into account the two mentioned developments. According to the first development, two major flight-vehicle classes are defined, pure aeroassisted re-entry vehicles at the one end, and airbreathing cruise and acceleration vehicles at the other end, with all possible shades in between. This is done in order to bring out the different degrees of importance of the aerothermodynamic phenomena for them. For the aerothermodynamics of the second vehicle class the fact that the outer surfaces are radiation cooled, is especially taken into account. Radiation cooling governs the thermal state of the surface, and hence all thermal surface effects. At the center of attention is the flight in the earth atmosphere at speeds below approximately 8.0 km/s and at altitudes below approximately 100.0 km.

The second development is taken into account only indirectly. The reader will not find much in the book about the basics of discrete numerical methods. Emphasis was laid on the discussion of flow physics and thermo-chemical phenomena, and on the provision of simple methods for the approximate quantification of the phenomena of interest and for plausibility checks of data obtained with numerical methods or with ground-simulation facilities. To this belongs also the introduction of the Rankine-Hugoniot-Prandtl-Meyer-(RHPM-) flyer as highly simplified configuration for illustration and demonstration purposes.

The author believes that the use of the methods of numerical aerothermodynamics permits much deeper insights into the phenomena than was possible before. This then warrants a good overall knowledge but also an eye for details. Hence, in this book results of numerical simulations are discussed in much detail, and two major case studies are presented. All this is done in view also of the multidisciplinary implications of aerothermodynamics.

The basis of the book are courses on selected aerothermodynamic design problems, which the author gave for many years at the University of Stuttgart, Germany, and of course, the many years of scientific and industrial work of the author on aerothermodynamics and hypersonic flight vehicle design problems. The book is intended to give an introduction to the basics of aerothermodynamics for graduate students, doctoral students, design and development engineers, and technical managers. The only prerequisite is the knowledge of the basics of fluid mechanics, aerodynamics, and thermodynamics.

The first two chapters of introductory character contain the broad vehicle classification mentioned above and the discussion of the flight environment. They are followed by an introduction to the problems of the thermal state of the surface, especially to surface radiation cooling. These are themes, which reappear in almost all the remaining chapters. After a review of the issues of transport of momentum, energy and mass, real-gas effects as well as inviscid and viscous flow phenomena are treated. In view of the importance for airbreathing hypersonic flight vehicles, and for the discrete numerical methods of aerothermodynamics, much room is given to the topic of laminar-turbulent transition and turbulence. Then follows a discussion of strong-interaction phenomena. Finally a overview over simulation means is given, and also some supplementary chapters.

Throughout the book the units of the SI system are used, with conversions given at the end of the book. At the end of most of the chapters, problems are provided, which should permit to deepen the understanding of the material and to get a "feeling for the numbers".

Zorneding, April 2004 *E. H. Hirschel*

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E. H. H.

Table of Contents

1 Introduction

In this book basics of aerothermodynamics are treated, which are of importance for the aerodynamic and structural layout of hypersonic flight vehicles. It appears to be useful to identify from the begin classes of hypersonic vehicles, because aerothermodynamic phenomena can have different importance for different vehicle classes. This holds especially for what is usually called "heat loads". In this book we introduce the "thermal state of the surface", which encompasses (and distinguishes between) thermal surface effects on wall and near-wall viscous-flow and thermo-chemical phenomena, and thermal (heat) loads on the structure.

1.1 Classes of Hypersonic Vehicles and their Aerothermodynamic Peculiarities

The scientific and technical discipline "aerothermodynamics" is multidisciplinary insofar as aerodynamics and thermodynamics are combined in it. However, recent technology work for future advanced space transportation systems has taught that "aerothermodynamics" should be seen from the beginning in an even larger context.

In aircraft design, a century old design paradigm exists, which we call Cayley's design paradigm, after Sir George Cayley (1773 - 1857), one of the early English aviation pioneers [1]. This paradigm still governs thinking, processes and tools in aircraft design, but also in spacecraft design. It says, that one ought to assign functions like lift, propulsion, trim, pitch and yaw stabilization and control, et cetera, plainly to corresponding subsystems, like the wing, the engine (the propulsion system), the tail unit, et cetera. These subsystems and their functions should be coupled only weakly and linearly. Then one is able to treat and optimize each subsystem with its function, more or less independent of the others, and nevertheless treats and optimizes the whole aircraft which integrates all subsystems.

For space planes, either re-entry systems, or cruise/acceleration systems (see the classification below), Cayley's paradigm holds only partly. So far this was more or less ignored. But if future space-transportation systems (and also hypersonic aircraft) are to be one order of magnitude more cost-effective than now, it must give way to a new paradigm. This should be possible because of the rise of computer power, provided that proper multidisciplinary simulation and optimization methods can be developed and brought into practical use [2].

It is not intended to introduce such a new paradigm in this book. However, it is tried to present and discuss aerothermodynamics in view of the major roles of it in hypersonic vehicle design, which reflects the need for such a new paradigm.

Different hypersonic vehicles pose different aerothermodynamic design problems. In order to ease the discussion, four major classes of hypersonic vehicles are introduced[1]. These are, with the exception of class 4, classes of aeroassisted vehicles, i. e. vehicles, which fly with aerodynamic lift in the earth atmosphere at altitudes below approximately 100.0 km, and with speeds below 8.0 km/s, Fig. 1.1.

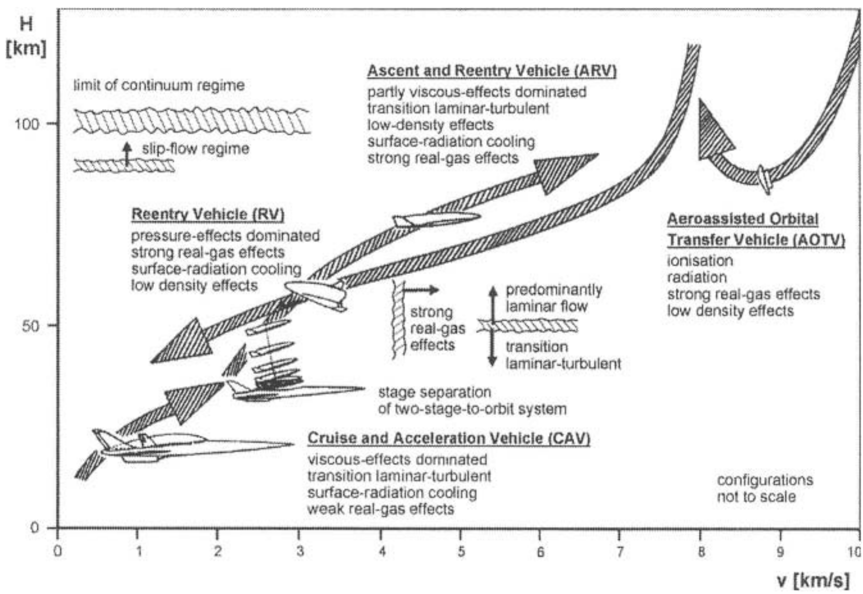

Fig. 1.1. The four major classes of hypersonic vehicles and some characteristic aerothermodynamic phenomena [4].

Of the mentioned vehicles so far only the Space Shuttle (and BURAN) actually became operational. All other are hypothetical vehicles or systems, which have been studied and/or developed to different degrees of completion [5]. The four classes are:

[1] A detailed classification of both civil and military hypersonic flight vehicles is given in [3].

1. Winged re-entry vehicles (RV), like the US Space Shuttle and the X-38[2], the Russian BURAN, the European HERMES, the Japanese HOPE. RV-type flight vehicles are launched typically by means of rocket boosters, but can also be the rocket propelled upper stages of two-stage-to-orbit (TSTO) space-transportation systems like SÄNGER, STAR-H, RADIANCE, MAKS.
2. Cruise and acceleration vehicles with airbreathing propulsion (CAV), like the lower stages of TSTO systems, e. g., SÄNGER, STAR-H, RADIANCE, but also hypothetical hypersonic air transportation vehicles (Orient Express, or the SÄNGER lower stage derivative). Flight Mach numbers would lie in the ram propulsion regime up to $M_\infty = 7$, and the scram propulsion regime up to $M_\infty = 12$ (to 14).
3. Ascent and re-entry vehicles (in principle single-stage-to-orbit (SSTO) space-transportation systems) with airbreathing (and rocket) propulsion (ARV), like the US National Aerospace Plane (NASP/X30), Oriflamme, HOTOL, and the Japanese Space Plane. The upper stages of TSTO-systems and purely rocket propelled vehicles, like Venture Star/X33, FESTIP FSSC-01, FSSC-15 et cetera are not ARV-type flight vehicles, because with their large thrust at take-off they do not need low-drag airframes.
4. Aeroassisted orbital transfer vehicles (AOTV), also called Aeroassisted Space Transfer Vehicles (ASTV), see, e. g., [6].

Each of the four classes has specific aerothermodynamic features and multidisciplinary design challenges. These are summarized in Table 1.1.

Without a quantification of features and effects we can already say, see also Fig.1.1, that for CAV- and ARV-type flight vehicles viscosity effects, notably laminar-turbulent transition and turbulence (which occur predominantly at altitudes below approximately 40.0 to 60.0 km) play a major role, while thermo-chemical effects are very important with RV-, ARV-, and AOTV-type vehicles. With the latter, especially plasma effects (ionization, radiation emission and absorption) have to be taken into account [6].

In Table 1.1 aerothermodynamic and multidisciplinary design features of the four vehicle classes are listed. The main objective of this list is to sharpen the perception, that for instance a CAV-type flight vehicle, i. e. an airbreathing aeroassisted system, definitely poses an aerothermodynamic (and multidisciplinary) design problem quite different from that of a RV-type vehicle. The CAV-type vehicle is aircraft-like, slender, flies at small angles of attack, all in contrast to the RV-type vehicle. The RV-type flight vehicle is a pure re-entry vehicle, which is more or less "only" a deceleration system,

[2] The X-38 is NASA's demonstrator of the previously planned crew rescue vehicle of the International Space Station.

Table 1.1. Comparative consideration of the aerothermodynamic features and multidisciplinary design features of four major classes of hypersonic vehicles.

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

however not a ballistic one. Therefore it has a blunt shape, and flies at large angles of attack in order to increase the effective bluntness[3].

Thermal loads always must be considered together with the structure and materials concept of the respective vehicle, and its passive or active cooling concept. As will be discussed later, the major passive cooling means for outer surfaces is surface-(thermal-)radiation cooling [8]. The thermal management of a CAV-type or ARV-type flight vehicle must take into account all thermal loads (heat sources), cooling needs and cooling potentials of airframe, propulsion system, sub-systems and cryogenic fuel system.

1.2 RV-Type and CAV-Type Flight Vehicles as Reference Vehicles

In the following chapters we refer to RV-type and CAV-type flight vehicles as reference vehicles. They represent the two principle vehicle classes on which we, regarding aerothermodynamics, focus our attention. ARV-type vehicles combine their partly contradicting configurational demands, whereas AOTV-type vehicles are at the fringe of our interest. Typical shapes of RV-type and CAV-type vehicles are shown in Fig. 1.2.

Typical flight Mach number and angle of attack ranges as function of the altitude of the Space Shuttle, [11], and the SÄNGER space-transportation system, [12], up to stage separation are given in Fig. 1.3. During the re-entry flight of the Space Shuttle the angle of attack remains larger than 20° down to $H \approx 35.0\ km$, where the Mach number is $M_\infty \approx 5$. SÄNGER on the other hand has an angle of attack below $\alpha = 10°$, before the stage separation at $M_\infty \approx 7$ occurs.

The flight Mach-number, the flight altitude, and the angle of attack ranges govern many of the aerothermodynamic phenomena. We illustrate the determining characteristics with the help of the RHPM-flyer, Chapter 11, which is a sufficient good approximation of RV-type and CAV-type flight vehicles, Table 1.2 and 1.3. For a convenient restitution of the data we use triplets of M_∞, H and α which are not necessarily present in Fig. 1.3. For the same reason the ratio of specific heats was chosen to be $\gamma = 1.4$, and the exponent in the power law of the viscosity, Sub-Section 4.2.2, to be $\omega_\mu = 0.65$.

We observe from the Tables 1.2 and 1.3 the following tendencies, see also Section 2.1:

- RV-type flight vehicles are characterized by a strong flow compression on the windward side, resulting in $M_w = 1.76$. In reality we have even a large

[3] We note that, for instance, future RV-type flight vehicles may demand large down and cross range capabilities (see some of the FESTIP study concepts [7]). Then Aerodynamic lift/drag "small" for RV-type vehicles in Table 1.1 actually should read "small to medium".

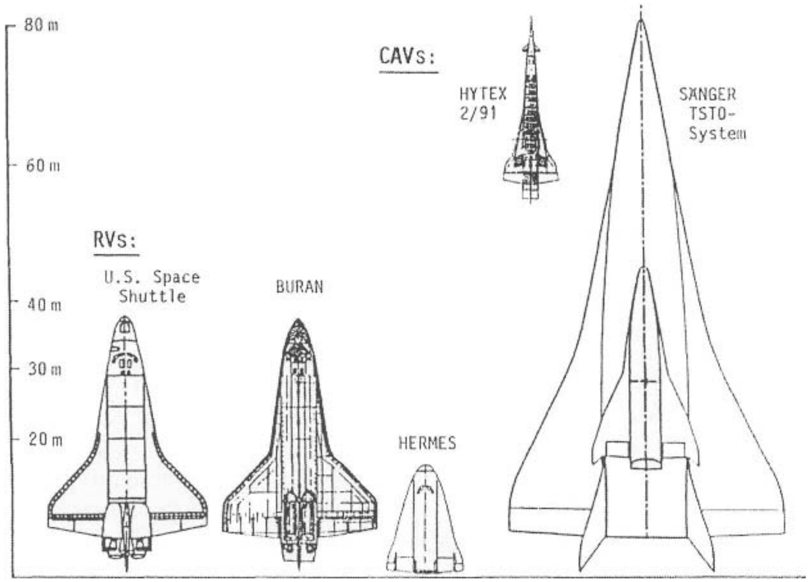

Fig. 1.2. Shape (planform) and size of hypersonic flight vehicles of class 1 (RV-type flight vehicles) and 2 (CAV-type flight vehicles) [9]. HYTEX: experimental vehicle studied in the German Hypersonics Technology Programme [10].

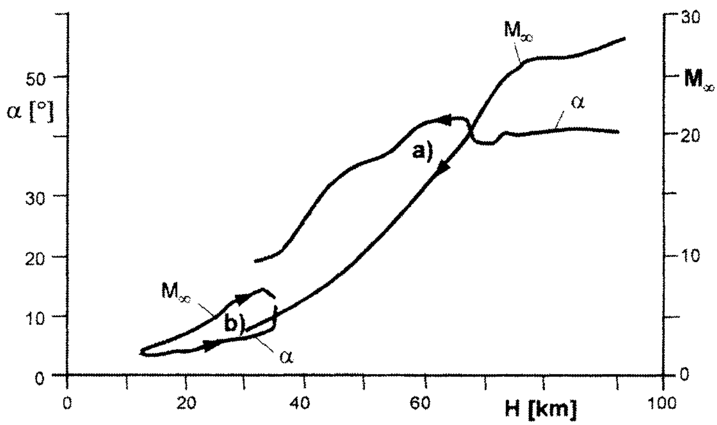

Fig. 1.3. Flight Mach number M_∞ and angle of attack α of **a**) the Space Shuttle, [11], and **b**) the two-stage-to-orbit space-transportation system SÄNGER up to stage separation, [12], as function of the flight altitude H.

Table 1.2. Flow parameters on the windward (w) and the lee (l) side of the RHPM-RV-flyer at 70.0 km altitude and an angle of attack $\alpha = 40°$, $\gamma = 1.4$, $\omega_\mu = 0.65$. The flow parameters are constant along the lower and the upper surface.

Location	M	T	p	ρ	Re^u_∞
∞	20	$219.69\ K$	$5.52\ Pa$	$8.75 \cdot 10^{-4}\ kg/m^3$	$3.62 \cdot 10^4\ m^{-1}$
w	1.76	$50.0\, T_\infty$	$295.0\, p_\infty$	$5.9\, \rho_\infty$	$0.29\, Re^u_\infty$
l	$\to \infty$	$\to 0\, T_\infty$	$\to 0\, p_\infty$	$\to 0\, \rho_\infty$	$\to 0\, Re^u_\infty$

Table 1.3. Flow parameters on the windward (w) and the lee (l) side of the RHPM-CAV-flyer at 30.0 km altitude and an angle of attack $\alpha = 7°$, $\gamma = 1.4$, $\omega_\mu = 0.65$. The flow parameters are constant along the lower and the upper surface.

Location	M	T	p	ρ	Re^u_∞
∞	6	$226.51\ K$	$1.20 \cdot 10^3\ Pa$	$1.842 \cdot 10^{-2}\ kg/m^3$	$2.26 \cdot 10^6\ m^{-1}$
w	5	$1.36\, T_\infty$	$2.72\, p_\infty$	$2.0\, \rho_\infty$	$1.59\, Re^u_\infty$
l	7.19	$0.72\, T_\infty$	$0.32\, p_\infty$	$0.45\, \rho_\infty$	$0.57\, Re^u_\infty$

subsonic pocket there. During a Space Shuttle re-entry one has typically at maximum $M_w \approx 2.5$, and mostly $M_w < 2$, [13]. The strong compression leads to large temperatures at still moderate densities, so that high-temperature real-gas effects are present[4], Chapter 5.

The unit Reynolds number Re^u is smaller than that at infinity. The boundary layer will be laminar at this altitude and it is at most a low supersonic boundary layer. Laminar-turbulent transition, Chapter 8, will happen only at altitudes below 60.0 to 40.0 km, where the boundary layer is also at most a low supersonic boundary layer. Due to the small unit Reynolds number the boundary layer is thick, Chapter 7, and hence radiation cooling is effective, Chapter 3.

On the lee-side it is indicated that the Prandtl-Meyer expansion limit, Chapter 6, has been reached. This does not match reality, but we can conclude that there no high-temperature real-gas effects are present, except for possible non-equilibrium frozen flow coming from the stagnation-point region. The boundary layer is extremely thick, radiation cooling is very effective.

- At CAV-type flight vehicles, due to the flight at small angle at attack, no large compression effects occur. We find them only in the blunt nose region and possibly at (swept) leading edges, ramps and control surfaces. High-temperature real-gas effects will essentially be restricted to these con-

[4] The use of $\gamma = 1.4$ of course gives much too high temperatures. With $\gamma = 1.25$ one gets $T_w \approx 25.0\ T_\infty$, which is more realistic, but does not change our conclusion.

figuration parts and to the boundary layers. They will increase of course with increasing flight speed.
On the windward side the Mach number is slightly below M_∞, on the lee side slightly above. The boundary layers are hypersonic boundary layers. The unit Reynolds numbers are large enough, so that laminar-turbulent transition will happen. The boundary layers are thick enough for an effective radiation cooling.

1.3 The Objectives of Aerothermodynamics

The aerothermodynamic design process is embedded in the vehicle design process. Aerothermodynamics has, in concert with the other disciplines, the following objectives:

1. Aerothermodynamic shape definition, which has to take into account the thermal state of the surface [14], if, for instance, it strongly influences the drag of the vehicle (CAV, ARV), or the performance of a control surface (all classes):
   a) Provision of aerodynamic performance, flyability and controllability on all trajectory elements (all vehicle classes).
   b) Aerothermodynamic airframe/propulsion integration for rocket propelled (RV, ARV) and especially airbreathing (CAV) vehicles.
   c) Aerothermodynamic integration of reaction control systems (RV, ARV, AOTV).
   d) Aerothermodynamic upper stage integration and separation for TSTO vehicles.
2. Aerothermodynamic structural loads determination for the layout of the structure and materials concept, the sizing of the structure, and the external thermal protection system (TPS) or the internal thermal insulation system, including possible active cooling systems for the airframe:
   a) Determination of mechanical loads (surface pressure, skin friction), both as static and dynamic loads, especially also acoustic loads.
   b) Determination of thermal loads for both external and internal surfaces/structures.
3. Surface properties definition (external and internal flowpath):
   a) In view of external surface-radiation cooling, the important "necessary" surface property is radiation emissivity. It governs the thermal loads of structure and materials, but also the thermal-surface effects on the near-wall viscous-flow and thermo-chemical phenomena.