Ernst Heinrich Hirschel

Basics of Aerothermodynamics

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With 147 Figures

Springer

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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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Finally I wish to thank my wife for her support and her never exhausted patience.

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.

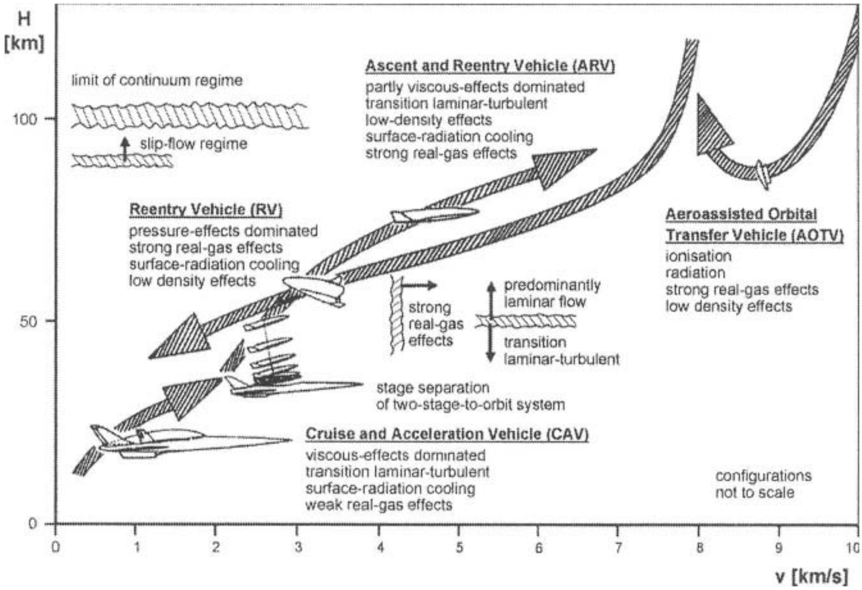

Fig. 1.1. The four major classes of hypersonic vehicles and some characteristic aerothermodynamic phenomena [4].

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:

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[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,

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[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

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[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".

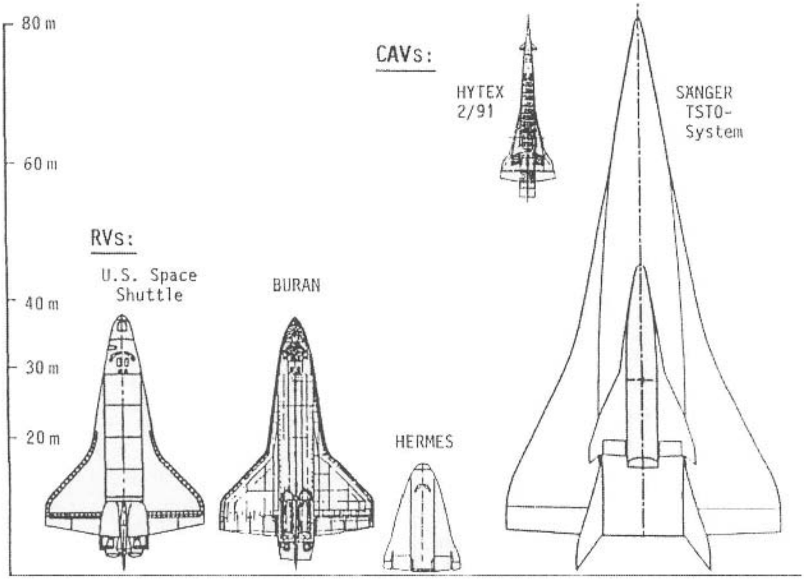

Fig. 1.2. Shape (planform) and size of hypersonic flight vehicles of class 1 (RV-type flight vehicles) and 2 (CAV-type flight vehicles) [9]. HYTEX: experimental vehicle studied in the German Hypersonics Technology Programme [10].

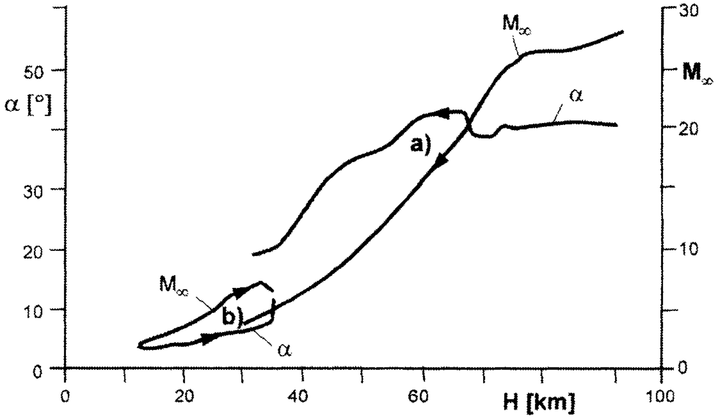

Fig. 1.3. Flight Mach number M_∞ and angle of attack α of **a**) the Space Shuttle, [11], and **b**) the two-stage-to-orbit space-transportation system SÄNGER up to stage separation, [12], as function of the flight altitude H.

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-

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[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.

b) "Permissible" surface properties are surface irregularities like roughness, waviness, steps, gaps et cetera in view of laminar-turbulent transition and turbulent boundary-layer flow. For CAV-type and ARV-type flight vehicles they must be "sub-critical" in order to avoid unwanted increments of viscous drag, and of the thermal state of the surface[5]. For RV-type vehicles surface roughness is an inherent matter of the layout of the thermal protection system (TPS). There especially unwanted increments of the thermal state of the surface are of concern on the lower part of the re-entry trajectory. In this context the problems of micro-aerothermodynamics on all trajectory segments are mentioned, which are connected to the flow, for instance, between tiles of a TPS or flow in gaps of control surfaces. All sub-critical, i. e. "permissible", values of surface irregularities should be well known, because surface tolerances should be as large as possible in order to minimize manufacturing cost.
Another "permissible" surface property is the surface catalytic behaviour, which should be as small as possible, in order to avoid unwanted increments of the thermal state of the surface, e. g., of the surface temperature. Usually surface catalytic behaviour, together with emissivity and anti-oxydation protection are properties of the surface coating of the airframe or the TPS material.

This short consideration shows that aerothermodynamics indeed must be seen not only in the context of aerodynamic design as such. It is an element of the truly multidisciplinary design of hypersonic flight vehicles, and must give answers and inputs to a host of design issues.

1.4 The Thermal State of the Surface and Radiation-Cooled Outer Surfaces as Focal Points

Under the "thermal state of the surface [14]" we understand the temperature of the gas at the surface, *and* the temperature gradient, respectively the heat flux, in it normal to the surface. As will be shown in Chapter 3, these are not necessarily those of and in the surface material. Regarding external surfaces we note, that these are, with some exceptions, in general only radiation cooled, if we consider aeroassisted space transportation vehicles or hypersonic aircraft flying in the earth atmosphere at speeds below approximately 8.0 km/s [8].

The thermal state of the surface thus is defined by

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[5] Sub-critical means that laminar-transition is not triggered prematurely, and that in turbulent flow neither skin friction nor heat transfer are enhanced by surface irregularities, Chapter 8.

- the actual temperature of the gas at the wall surface, T_{gw}, and the temperature of the wall, T_w, with $T_{gw} \equiv T_w$, if low-density effects (temperature jump) are not present,
- the temperature gradient in the gas at the wall, $\partial T/\partial n|_{gw}$, in direction normal to the surface[6], respectively the heat flux in the gas at the wall, q_{gw}, if the gas is a perfect gas or in thermo-chemical equilibrium, Chapter 5,
- and the temperature gradient in the material at the wall surface, $\partial T/\partial n|_w$, in (negative) direction normal to the surface, respectively the heat flux q_w (tangential gradients are also neglected). The heat flux q_w is not equal to q_{gw}, if radiation cooling is employed, Section 3.1.

If one considers a RV-type flight vehicle, the thermal state of the surface concerns predominantly the structure and materials layout of the vehicle, and not so much its aerodynamic performance. This is because the RV-type vehicle flies a "braking" mission, where the drag on purpose is large (blunt configuration, large angle of attack, Table 1.1). Of course, if a flight mission demands large down-range or cross-range capabilities in the atmosphere, this may change somewhat.

The situation is different for an (airbreathing) CAV-type flight vehicle, which like any aircraft is drag-sensitive, and where viscous effects, which are affected strongly by the thermal state of the surface, in general play an important role, Table 1.1.

This book puts emphasis on this fact by distinguishing between the classical "thermal (heat) loads", which are of importance for the structure and materials concept of a vehicle, and "thermal-surface effects", which concern wall and near-wall viscous-flow and thermo-chemical phenomena, Fig. 1.4. This holds for both the external and the internal flowpath of a vehicle.

Both thermal-surface effects and thermal loads are coupled directly to the necessary and permissible surface properties, which were mentioned in the previous section.

In the following Table 1.4 wall and near-wall viscous-flow and thermo-chemical phenomena as well as structure and materials issues are listed, which are influenced by the thermal state of the surface. Partly our knowledge of these phenomena is still limited. We note in any case that there are viscous phenomena, especially laminar-turbulent transition, which are influenced by both T_w and $\partial T/\partial n|_{gw}$. This is also true for catalytic surface recombination.

Regarding materials and structures we note first of all that "thermal loads" encompasses both the wall temperature T_w and the heat flux into

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[6] The temperature gradients, and hence the heat fluxes tangential to the surface, which in downstream direction appear especially with radiation cooled surfaces, are neglected in this consideration, but there might be situations, where this is not permitted. We neglect also slip-flow and non-equilibrium effects, which are discussed in Chapters 4 and 5.

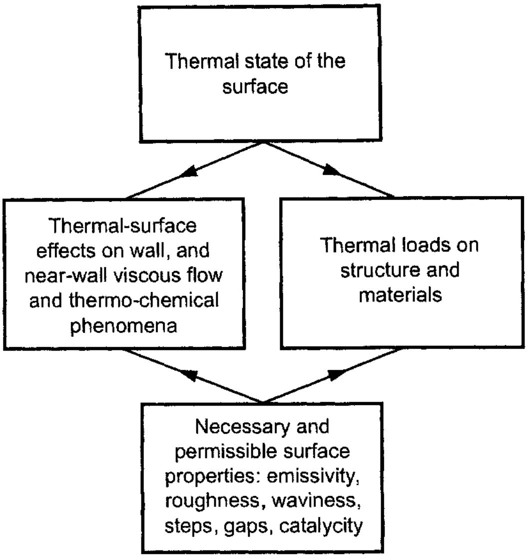

Fig. 1.4. The thermal state of the surface and its different aero-thermal design implications.

Table 1.4. Wall and near-wall viscous-flow/thermo-chemical phenomena, and structure and materials issues influenced by the thermal state of the surface (n is the direction normal to the surface, ( ) indicates indirect influence).

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

the wall q_w. The wall temperature T_w governs the choice of surface material (and coating) in view of strength and endurance, and $\partial T/\partial n|_w$ or q_w, for instance, as function of flight time, the thickness of the thermal protection system (TPS) of a RV-type flight vehicle.

In the Chapters 5, 7 and 8 emphasis will be put on the discussion of the influence of the thermal state of the surface, especially in presence of radiation cooling, on wall, and near-wall thermo-chemical and viscous-flow phenomena. This influence, of course, is additional to that of the basic parameters Reynolds number, Mach number, stream-wise and cross-wise pressure gradients, et cetera.

1.5 Scope and Content of the Book

The aerodynamic and aerothermodynamic design of flight vehicles presently is undergoing large changes regarding the tools used in the design processes. Discrete numerical methods of aerothermodynamics find their place already in the early vehicle definition phases. This is a welcome development from the viewpoint of vehicle design, because only with their use the necessary completeness and accuracy of design data can be attained. However, as will be shown and discussed in this book, computational simulation still suffers, like that with other analytical methods, and of course also ground-facility simulation, under the insufficient representation of real-gas and of turbulence phenomena. This is a shortcoming, which in the long run has to be overcome.

It remains the problem that computational simulation gives results on a high abstraction level. This is similar with the application of, for instance, computational methods in structural design. The user of numerical simulation methods therefore must have very good basic knowledge of both the phenomena he wishes to describe and their significance for the design problem at hand.

Therefore this book has the aim to foster:

- the knowledge of aerothermodynamic phenomena regarding their significance in vehicle design,
- the understanding of their qualitative dependence on flight parameters, vehicle geometry, et cetera,
- and their quantitative description.

As a consequence of this the classical approximate methods, and also the modern discrete numerical methods, in general will not be discussed in detail. The reader is referred either to the original literature, or to hypersonic monographs, which introduce to their basics in some detail, for instance [15], [16]. However, approximate methods, and very simple analytical considerations will be employed where possible to give basic insights and to show basic trends. For this reason also a highly simplified flight-vehicle configuration, the

Rankine-Hugoniot-Prandtl-Meyer- (RHPM-) flyer is introduced. It basically is only an infinitely thin flat plate at angle of attack. The flow past it is determined by means of simple shock-expansion theory. In all chapters also results of computational or ground-facility simulation as well as flight data will be used to broaden the picture.

The following Chapter 2 treats the flight environment, which is in the frame of this book predominantly the earth's atmosphere below approximately 100.0 *km* altitude. Chapter 3 is devoted to the discussion of the thermal state of the vehicle surface. Especially the phenomena connected to radiation cooling of outer surfaces are considered.

Chapter 4 gives the basic mathematical formulations regarding transport of mass, momentum and energy. Emphasis is put on the presentation and discussion of similarity parameters, and of the boundary conditions at the vehicle surface. They govern, together with the free-flight parameters and the vehicle geometry, all what happens in the flow past the vehicle and on the surface of the vehicle, the latter being the major concern of the vehicle designer.

Chapters 5, 6, 7, 8, and 9 then treat the topics real-gas phenomena, inviscid phenomena, attached high-speed viscous flow, laminar-turbulent transition and turbulence, and strong-interaction phenomena. Concerning wall-near viscous-flow and thermo-chemical phenomena we put emphasis on the discussion of the influence of thermal-surface effects, i. e., the influence of the thermal state of the surface on these phenomena.

A discussion of computational and ground-facility simulation means follows in Chapter 10. Again we will not go into details, for instance of algorithms or of wind-tunnels and wind-tunnel measurement techniques. Instead basic potentials and deficits of the simulation means will be considered, including problems of in-flight simulation.

Chapter 11 introduces the RHPM-flyer, in Chapter 12 we collect the governing equations of hypersonic flows in general coordinates. Both chapters serve as reference chapters for the forgoing ones. The book closes with constants, functions et cetera, symbols, the author and the subject index, and permissions.

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2 The Flight Environment

Hypersonic flight either of space-transportation systems or of hypersonic aircraft in the earth atmosphere is in the focal point of the book. Hence the flight environment considered here is that which the earth atmosphere poses. The basic features and properties are discussed, and references are given for detailed information.

2.1 The Earth Atmosphere

The earth atmosphere consists of several layers, the troposphere from sea level up to approximately 10.0 km, the stratosphere between 10.0 km and 50.0 km, the mesosphere between 50.0 km and 80.0 km, and the thermosphere above approximately 80.0 km altitude, Fig. 2.1. The weather phenomena occur mainly in the troposphere, and consequently the fluctuations there mix and disperse introduced contaminants. These fluctuations are only weakly present at higher altitudes.

The stratosphere is characterized by a temperature plateau around 220.0 K to 230.0 K, in the mesosphere it becomes colder, in the thermosphere the temperature rises fast with altitude. Ecologically important is the altitude between 18.0 and 25.0 km with the vulnerable ozone layer.

The composition of the atmosphere can be considered as constant in the homosphere, up to approximately 100.0 km altitude. In the heterosphere, above 100.0 km altitude, it changes with altitude. This is important especially for computational simulations of aerothermodynamics. Note that also around 100.0 km altitude the continuum domain ends (Section 2.3).

It should be mentioned, that these numbers are average numbers, which partly depend strongly on the degree of geographical latitude of a location, and that they are changing with time (seasons, atmospheric tides, sun-spot activities). A large number of reference and standard atmosphere models is discussed in [1], where also model uncertainties and limitations are noted.

In aerothermodynamics we work usually with the U. S. standard atmosphere [2], in order to determine static pressure (p_∞), density (ρ_∞), static temperature (T_∞) et cetera as function of the altitude, Table 2.1. The 15°C standard atmosphere assumes a temperature of 15°C at sea level. A graphical view of some properties of the standard atmosphere is given in Fig. 2.1.

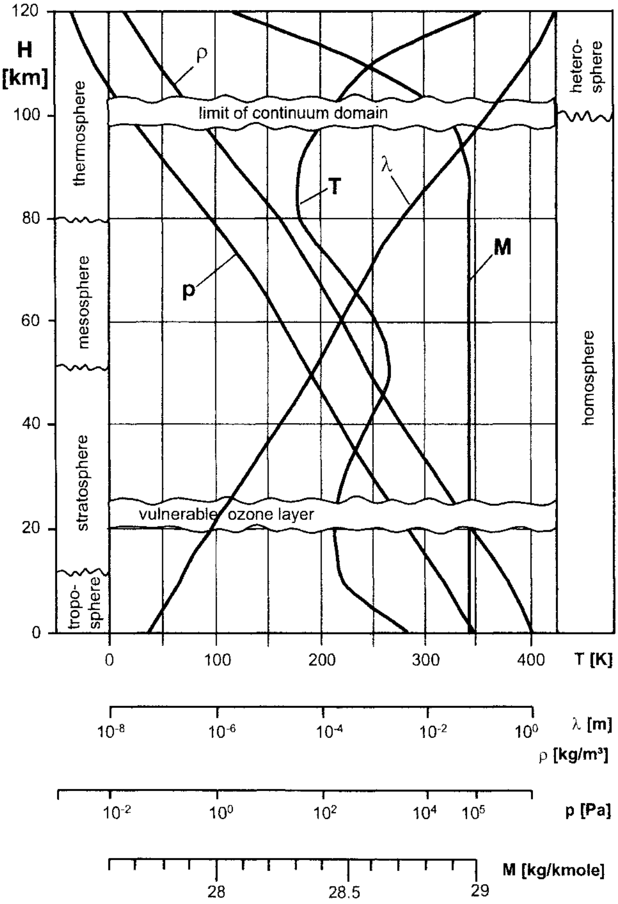

Fig. 2.1. Atmospheric layers and some properties of the atmosphere as function of the altitude, based on [2] (see also Table 2.1).

Uncertainties in atmospheric data influence guidance and control of a hypersonic flight vehicle. Large density fluctuations, which predominantly can occur in approximately 60.0 to 80.0 *km* altitude, must be compensated during, for example, a re-entry flight, otherwise a (down) range deviation would occur[1]. A 25 per cent smaller density than assumed at that altitude would lead, without correcting measures, to an approximately 100.0 *km* larger downstream range [3].

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[1] This is a phenomenon which is primarily governed by the vehicle drag. The flight-path angle down to approximately 60.0 *km* altitude is 2° or less, so that the vehicle flies almost a circular trajectory. The drag then is an aerothermodynamic drag whereas the aerodynamic lift is initially only a fraction of the effective lift.

Table 2.1. Properties of the 15°*C* U. S. standard atmosphere as function of the altitude, [2].

Altitude H [*km*]	Temperature T [*K*]	Pressure p [*Pa*]	Density ρ [kg/m^3]	Mean free path λ [*m*]	Mean molecular weight M [*kg/kg-mole*]
0.0	288.150	$1.013 \cdot 10^5$	$1.225 \cdot 10^0$	$6.633 \cdot 10^{-8}$	28.9644
10.0	225.320	$2.641 \cdot 10^4$	$4.084 \cdot 10^{-1}$	$1.990 \cdot 10^{-7}$	28.9644
20.0	217.359	$5.531 \cdot 10^3$	$8.865 \cdot 10^{-2}$	$9.165 \cdot 10^{-7}$	28.9644
30.0	226.506	$1.198 \cdot 10^3$	$1.842 \cdot 10^{-2}$	$4.411 \cdot 10^{-6}$	28.9644
40.0	250.334	$2.874 \cdot 10^2$	$3.999 \cdot 10^{-3}$	$2.032 \cdot 10^{-5}$	28.9644
50.0	270.650	$7.978 \cdot 10^1$	$1.027 \cdot 10^{-3}$	$7.912 \cdot 10^{-5}$	28.9644
60.0	255.758	$2.244 \cdot 10^1$	$3.056 \cdot 10^{-4}$	$2.658 \cdot 10^{-4}$	28.9644
70.0	219.690	$5.518 \cdot 10^0$	$8.751 \cdot 10^{-4}$	$9.285 \cdot 10^{-4}$	28.9644
80.0	182.839	$1.036 \cdot 10^0$	$1.974 \cdot 10^{-5}$	$4.117 \cdot 10^{-3}$	28.9644
90.0	183.921	$1.648 \cdot 10^{-1}$	$3.121 \cdot 10^{-6}$	$2.603 \cdot 10^{-2}$	28.9618
100.0	212.504	$3.049 \cdot 10^{-2}$	$4.982 \cdot 10^{-7}$	$1.625 \cdot 10^{-1}$	28.8674
110.0	258.017	$7.379 \cdot 10^{-3}$	$9.823 \cdot 10^{-8}$	$8.156 \cdot 10^{-1}$	28.5570
120.0	360.325	$2.556 \cdot 10^{-3}$	$2.395 \cdot 10^{-8}$	$3.288 \cdot 10^0$	28.0673

For in-flight tests, for instance for vehicle-parameter identification purposes, or to obtain data on aerothermodynamic or other phenomena, it is mandatory to have highly accurate instantaneous "air data" on the trajectory in order to correlate measured parameters, Section 10.4. The air data are the thermodynamic data p_∞, T_∞, ρ_∞, and the vehicle speed vector $\underline{v}_\infty$ relative to the surrounding air space.

The atmosphere with its properties determines the free-stream parameters of a flight vehicle. These in turn govern the aerothermodynamic phenomena and the aerodynamic performance. We give a short overview in Figs. 2.2 to 2.4 [4] over the main free-stream parameters and some aerothermodynamic phenomena for the altitude domain $0.0\ km \leq H \leq 65.0\ km$, and the flight-speed domain $0.0\ km/s \leq v_\infty \leq 7.0\ km/s$. Indicated are nominal design points of the supersonic passenger aircraft Concorde, of four reference concepts LK1 to LK4 of a German hypersonic technology study [5], of the SÄNGER lower stage (staging condition) [6], and of the X-30 (cruise) [7]. Typical trajectory data of re-entry vehicles (US Space Shuttle, HERMES) are included, too.

Fig. 2.2 shows iso-Mach-number lines. These lines are more or less parallel to iso-speed lines. Turbo propulsion is possible up to $M_\infty \approx 3$, i. e. $v_\infty \approx 1.0\ km/s$, ram-jet propulsion between $3 \lesssim M_\infty \lesssim 7$, i. e. $1.0\ km/s \lesssim v_\infty \lesssim 2.0\ km/s$, and finally scram-jet propulsion between $4 \lesssim M_\infty \lesssim 12$ to 14, i. e. $1.2\ km/s \lesssim v_\infty \lesssim 4.0$ to $4.5\ km/s$.

Iso-unit Reynolds-number lines are at larger altitudes approximately parallel to iso-altitude lines. They show that at flight below approximately 50.0

km altitude boundary layers will be predominantly turbulent, Fig. 2.3, if the unit Reynolds number $Re^u_\infty = \rho_\infty u_\infty / \mu_\infty \approx 10^5\ m^{-1}$ is taken, with due reservations, as zero-order criterion. This means that the design of airbreathing flight vehicles (CAV-type vehicles) always has to cope with laminar-turbulent transition and turbulence. The laminar portion at the front part of a flight vehicle will be small at small altitudes and finally will extend over the vehicle length when $Re^u_\infty \approx 10^5\ m^{-1}$ is approached. On RV-type flight vehicles boundary layers are laminar during re-entry flight above approximately 60.0 to 40.0 km altitude, i. e. especially in the domain of large high-temperature real-gas effects and large thermal loads.

Included in Fig. 2.3 are also lines of constant total temperature (equilibrium real gas). They indicate that with increasing speed thermal loads indeed become a major design problem of airframes of hypersonic flight vehicles, and of airbreathing propulsion systems.

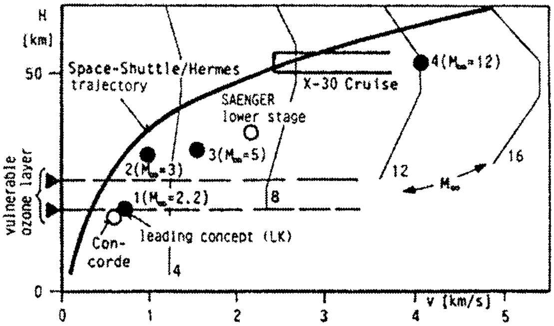

Fig. 2.2. Hypersonic flight-vehicle concepts in the velocity-altitude map ($v \equiv v_\infty$) with flight Mach numbers M_∞, [4] (based on [8]).

Fig. 2.4 finally shows that at flight speeds below $v_\infty \approx 0.8\ km/s$ air can be considered as a calorically and thermally perfect gas. For $0.8\ km/s \lessapprox v_\infty \lessapprox 2.6\ km/s$ vibration excitation must be taken into account. Above $v_\infty \approx 2.5\ km/s$ first dissociation of oxygen and then of nitrogen occurs. The dissociation of both gas constituents depends strongly on the flight altitude. At altitudes below $\approx 25.0\ km$ we can expect in general equilibrium, above it non-equilibrium real-gas behaviour. These statements are only of approximate validity, in reality flight vehicle form and size play a major role.

2.2 Atmospheric Properties and Models

The earth atmosphere is a gas consisting (if dry) of molecular nitrogen (N_2, 78.084 volume per cent), molecular oxygen (O_2, 20.946 volume per cent),

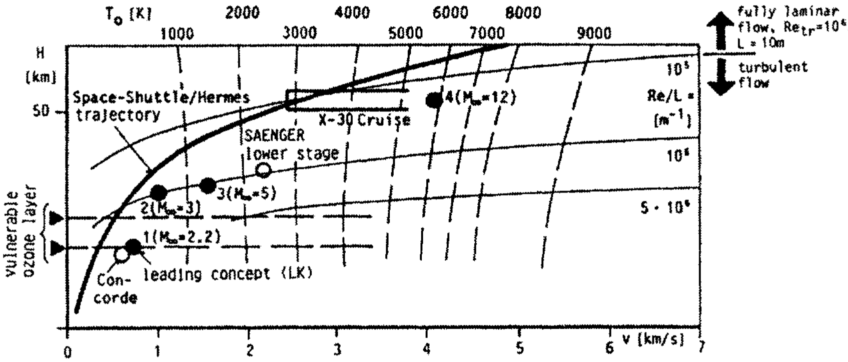

Fig. 2.3. Hypersonic flight-vehicle concepts in the velocity-altitude map with flight unit Reynolds numbers ($Re/L \equiv Re^u_\infty$), and equilibrium real-gas total temperatures T_o ($\equiv T_t$) [4] (based on [8]).

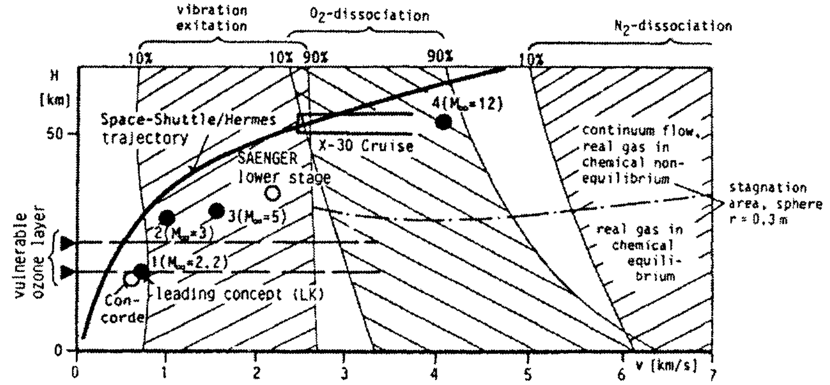

Fig. 2.4. Hypersonic flight-vehicle concepts in the velocity-altitude map with high-temperature real-gas effects [4] (based on [8]).

argon (Ar, 0.934 volume per cent), carbon dioxide (CO_2, 0.033 volume per cent), and some other spurious gases.

For our purposes we assume that the undisturbed air consists only of the molecules N_2 and O_2, with all three translational, and two rotational degrees of freedom of each molecule excited, Chapter 5. During hypersonic flight in the earth atmosphere this (model) air will be heated close to the flight vehicle due to compression and viscous effects. Consequently then first the (two) vibration degrees of freedom of the molecules become excited, and finally dissociation and recombination takes place. The gas is then a mixture of molecules and atoms. In aerothermodynamics at temperatures up to 8,000.0 K air can be considered as a mixture of the five species [9], [10]:

N_2, N, O_2, O, NO.