Ernst Heinrich Hirschel

Basics of Aerothermodynamics

Second, Revised Edition

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Preface to the Second Edition

The last decade has seen the successful performance at hypersonic speed of ramjet and scramjet propulsion systems. This probably is the true dawn of airbreathing hypersonic flight. In any case, these recent accomplishments are the motivation to emphasize the importance of viscous effects in this second edition of the Basics of Aerothermodynamics.

The flow past airbreathing hypersonic flight vehicles is viscosity-effects dominated. These effects concern the viscous drag (a large part of the total drag), the integrated aerothermodynamic airframe/propulsion flow path including the engine's air inlets and nozzles, and the performance of aerodynamic trim, stabilization and control surfaces. In the flow past re-entry vehicles viscous effects are mainly important at trim and control surfaces. The viscous drag there—on a large part of the re-entry trajectory—is only a small part of the total drag.

In view of vehicle design and development an important aspect needs to be considered. The surface of the external flow path of an hypersonic vehicle of any kind is mainly surface-radiation cooled, at very high Mach numbers in particular cases also actively cooled. The ensuing wall temperatures and heat fluxes in the gas at the wall—*the thermal state of the wall*—are variable all over the vehicle's surface. Many flow phenomena including laminar-turbulent transition depend strongly on the thermal state of the wall—*thermal surface effects*. The thermal state of the surface in turn depends strongly on the state of the boundary layer, laminar, transitional, or turbulent.

The problem is that today the flow simulation in ground facilities of any type does not allow to take into account the thermal state of the surface of a complete flight vehicle model. This also holds for hot model surfaces which are not radiation cooled. The hot experimental technique is in its infancies. How far it can be developed, is an open question. Of course, the discrete numerical methods of aerothermodynamics are on the rise. But for quite a time to come the computational simulation will not take over completely the tasks of the ground-facility simulation. This holds for the verification of the aerodynamic shape design as well as for the generation of the aerothermodynamic data set.

The first edition of the Basics of Aerothermodynamics had already as focus—besides that on the classical gasdynamic and thermodynamic phenomena—that on the viscous phenomena in high-speed flow. And this in view of the fact that external vehicle surfaces are radiation cooled.

In this second edition the chapters with the classical topics remain basically untouched. The accessibility to some single topics is improved. The sections and chapters devoted to viscous effects are, as before, complemented with the discussion of thermal surface effects, partly however in more detail. A final chapter is added, which is completely devoted to recent results regarding thermal surface effects from both theoretical/numerical and experimental investigations.

The author hopes that in this way the knowledge is enhanced about viscous effects in the flow past hypersonic flight vehicles. This holds in particular for airbreathing vehicles, but also for re-entry vehicles. Hypersonic glide vehicles have the same design problems as airbreathing vehicles, however without the particularities of the propulsion system's integration.

The aim of the book is to convey to the student a broad knowledge of all aspects of aerothermodynamics, in particular also of viscous effects. The vehicle designer in addition should become aware of where these effects are important and how they are to be quantified and simulated. This holds for both ground facility and computational simulation.

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Last not least, special thanks go to my wife for her support and her again never exhausted patience.

Ernst Heinrich Hirschel

Preface to the First Edition

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 in 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 aeroservoelasticity problems of the airframe, etc., 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 km/s and at altitudes below approximately 100 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 of 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 air-breathing 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 Ernst Heinrich Hirschel

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

Ernst Heinrich Hirschel

Table of Contents

1

Introduction

In this book basics of aerothermodynamics are treated, which are of importance for the aerodynamic and structure layout of hypersonic flight vehicles. It appears to be useful to identify from the beginning classes of hypersonic vehicles, because aerothermodynamic phenomena can have different importance for different vehicle classes. This holds in particular for what is usually called "viscous effects". In view of them we introduce in this book the "thermal state of the surface", which—besides the classical similarity parameters—governs "thermal surface effects" on wall and near-wall viscous-flow and thermo-chemical phenomena, as well as "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, etc., plainly to corresponding subsystems, like the wing, the engine (the propulsion system), the tail unit, etc. 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 are

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to be one order of magnitude more cost-effective than now, and airbreathing hypersonic aircraft are to become reality, 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 winged vehicles which fly with aerodynamic lift in the Earth atmosphere at altitudes below approximately 100 km, and with speeds below 8 km/s, Fig. 1.1.[2]

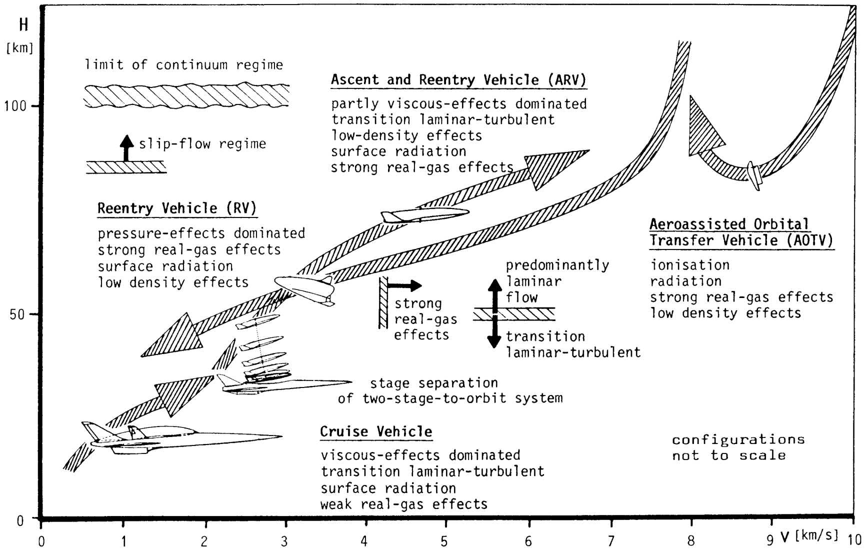

Fig. 1.1. The four major classes of hypersonic vehicles and some characteristic aerothermodynamic phenomena [4].

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

[2] In [5] non-winged re-entry vehicles (capsules) are considered as a separate vehicle class. Most prominent members of this class are APOLLO and SOYUZ. Capsules flying in the Earth atmosphere at altitudes below approximately 100 km, and with speeds below 8 km/s can be considered as belonging to class 1.

Of the below mentioned vehicles so far only the Space Shuttle Orbiter (the Russian BURAN flew only once) actually became—and was—operational. All other are hypothetical vehicles or systems, which have been studied and/or developed to different degrees of completion, see, e.g., [5]–[7]. The four classes are:

1. Winged re-entry vehicles (RV's), like the US Space Shuttle Orbiter and the X-38,[3] the Russian BURAN, the European HERMES, the Japanese HOPE. RV's 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's), 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 in the scram propulsion regime up to $M_\infty = 12$ (to 14).[4]
3. Ascent and re-entry vehicles (ARV's)—in principle single-stage-to-orbit (SSTO) space-transportation systems—with airbreathing (and rocket) propulsion 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 etc. are not considered to be ARV's, because with their large thrust at take-off they do not need low-drag airframes.
4. Aeroassisted orbital transfer vehicles (AOTV's), also called Aeroassisted Space Transfer Vehicles (ASTV's), see, e.g., [12].

Each of the four classes has specific aerothermodynamic features and multidisciplinary design challenges. These are summarized in Table 1.1.[5]

Without a quantification of features and effects we can already say, see also Fig.1.1, that for CAV's and ARV's (in their airbreathing propulsion mode) viscosity effects, notably laminar-turbulent transition and turbulence (which occur predominantly at altitudes below approximately 40 km to 60 km) play

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

[4] The experimental vehicles X-43A, [8], and X-51A, [9], were dedicated to the tests of scramjet (supersonic combustion ramjet) and ramjet propulsion systems. In the frame of HIFiRE, [10], HIFiRE-2 and HIFiRE-3 were scramjet flight experiments. Boost-glide vehicles go back to the X-20/Dyna-Soar, which has its roots in German studies during World War II [11]. Such vehicles can be counted as CAV's, however without a propulsion system.

[5] In Section 1.2 characteristic flow features of two particular flight vehicle classes are discussed in some detail.

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's)	Cruise and acceleration vehicles (CAV's)	Ascent and re-entry vehicles (ARV's)	Aeroassisted orbital transfer vehicles (AOTV's)
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	trim and control surfaces	inlet, nozzle/ afterbody, trim and control surfaces	inlet, nozzle/ afterbody, trim and control surfaces	trim and control devices
Special problems	large Mach number span	propulsion integration, thermal management	propulsion integration, opposing design requirements	plasma effects

a major role, whereas thermo-chemical effects are very important with RV's, ARV's (in their re-entry mode), and AOTV's. With the latter, in particular plasma effects in the bow-shock layer (ionization, radiation emission and absorption) have to be taken into account [12].

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, i.e., an airbreathing flight system, definitely poses an aerothermodynamic (and multidisciplinary) design problem quite different from that of a RV. The CAV is aircraft-like, slender, flies at small angles of attack, all in contrast to the RV. The RV is a pure re-entry vehicle, which is more or less "only" a deceleration system, 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.[6]

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 [14]. The thermal management of a CAV or ARV must take into account all thermal loads (heat sources), cooling needs and cooling potentials of airframe, propulsion system, subsystems, 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 the basics of aerothermodynamics—focus our attention. ARV's combine their partly contradicting configurational demands, whereas AOTV's are at the fringe of our interest. Typical shapes of some RV's and CAV's are shown in Fig. 1.2.

Characteristic flight Mach number and angle of attack ranges as function of the altitude of the Space Shuttle Orbiter, [15], and the SÄNGER TSTO space-transportation system, [16], up to stage separation are given in Fig. 1.3. (Basic trajectory considerations can be found in [5].) During the re-entry flight of the Space Shuttle Orbiter the angle of attack initially is approximately $\alpha = 40°$ and then remains larger than $\alpha = 20°$ down to $H \approx 35$ 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 ranges of the flight altitude H, the flight Mach-number M_∞, and the angle of attack α, together with a number of other vehicle features govern the

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[6] We note that, for instance, future RV's may demand large down and cross range capabilities (see some of the FESTIP study concepts [13] and also [5]). Then aerodynamic lift/drag "small" for RV's in Table 1.1 actually should read "small to medium".

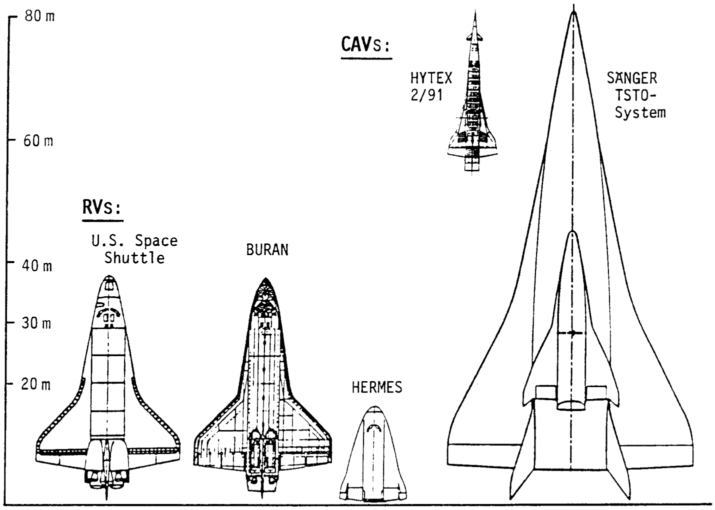

Fig. 1.2. Shape (planform) and size of hypersonic flight vehicles of class 1 (RV's) and class 2 (CAV's) [17]. HYTEX: experimental vehicle studied in the German Hypersonics Technology Programme [18].

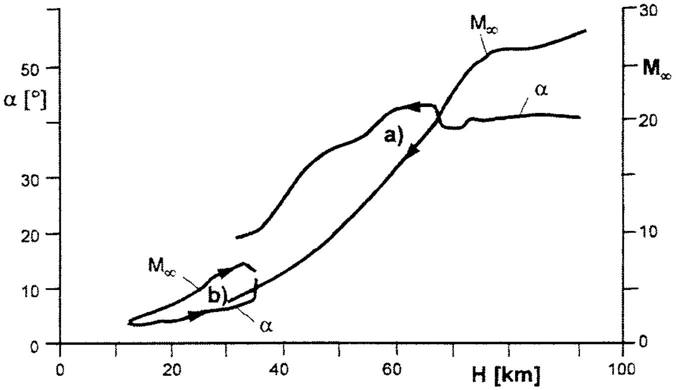

Fig. 1.3. Flight Mach number M_∞ and angle of attack α of a) the Space Shuttle Orbiter, [15], and b) the two-stage-to-orbit space-transportation system SÄNGER up to stage separation, [16], as function of the flight altitude H.

aerothermodynamic phenomena found at a hypersonic flight vehicle. We give an overview of these features together with some of the resulting typical flow features in Table 1.2 on page 9. The considered vehicles are the Space Shuttle (SS) Orbiter and the lower stage (LS) of SÄNGER, each at a characteristic trajectory point.

Regarding the flow features we look only at some of them found along the lower symmetry lines of the two vehicles. Apart from the nose region and the beginning of the boattailing ($x/L = 0.82$), the lower (windward) symmetry line of the Space Shuttle (SS) Orbiter has no longitudinal curvature. (The lower side of the vehicle is mostly flat at $0.12 \lessapprox x/L \lessapprox 0.82$, see, e.g., [5].) At the lower stage (LS) of SÄNGER we consider only the forebody up to the location of the beginning of the inlets of the propulsion system [5]. The lower side actually is a pre-compression ramp for the inlets. Apart from the nose region it is flat.

Vehicle surface properties We note first that the lower side of the SS Orbiter has, except for the nose region, a rough surface, given by the tiles and the gaps between them of the thermal protection system (TPS). The SÄNGER LS has a smooth surface. This is a necessity—regardless of the structure and materials concept of the vehicle—because the boundary layer must not be influenced negatively by the surface properties (permissible surface properties, Section 1.3).

Aerothermoelasticity Both the static and the dynamic aerothermoelasticity are important flight vehicle issues. For the SS Orbiter generally it can be stated that surface deformations are of such a small magnitude that the flow field past it is not affected. The situation is different at the SÄNGER LS forebody. There temperature differences exist between the lower and the upper side, Section 7.3. These differences may lead to a static deformation of the approximately 55 m long forebody with large consequences for the flow, in particular the inlet-onset flow, the thrust of the propulsion system and the aerodynamic forces and moments of the vehicle [5]. The same holds for the dynamic deformation of the forebody.

Atmospheric fluctuations are not of influence for the SS Orbiter on its high trajectory elements. There density uncertainties are a matter of concern, Section 2.1. Below 60 to 40 km altitude atmospheric fluctuations have an influence on the laminar-turbulent transition process. This holds for the Orbiter, but in particular for the SÄNGER LS, which flies at most at 33 km altitude. At the Orbiter the thermal loads are affected by the laminar-turbulent transition, whereas the drag increase does not matter.

Surface radiation cooling of external surfaces reduces the thermal loads to a degree that re-usable thermal protection systems (RV's) and hot primary structures (CAV's, partly found also at RV's), become possible at all, Chapter 3. The external surfaces of both the considered vehicles are radiation cooled, the SS Orbiter, however, only at the surface portions which are exposed to the free stream (windward side). The in Table 1.2 given emissivity coefficients (necessary surface properties, Section 1.3) are nominal ones. The real ones are of that order of magnitude. At non-convex surface portions, the (fictitious) emissivity coefficient is smaller, Sub-Section 3.2.5.

High-temperature real-gas effects are present in both the inviscid and the viscous flow field past the windward side of the SS Orbiter. They are due to the high total enthalpy and the strong compression of the air stream at the vehicle surface. In Fig. 2.4 it is indicated—although the here considered trajectory point lies just outside of the graph—that chemical non-equilibrium of the major constituents of air is present. Accordingly catalytic surface recombination is possible, Sub-Section 4.3.3, if the related permissible surface properties, Section 1.3, are exceeded. Then also heat transfer due to mass diffusion happens, in addition to the anyway present molecular heat transfer, Sub-Section 4.3.3.

At the SÄNGER LS high-temperature real-gas effects are small, Fig. 2.4. The total enthalpy of the free-stream in this case is much smaller than in the SS Orbiter case. Nevertheless, vibration excitation of O_2 and N_2 is present and—at most weak—dissociation of O_2. Hence surface catalytic recombination is not a topic and also not heat transfer by mass diffusion.

Low-density effects The Knudsen numbers for the two flight vehicles at the given trajectory points are such that no low-density effects occur, Fig. 2.6. Possible exceptions are air data gauges and measurement orifices.

Entropy layer The SS Orbiter has a blunt nose region and the SÄNGER LS a blunt nose. At a blunt configuration at supersonic or hypersonic flight speed due to the curved bow-shock surface an entropy layer appears, Sub-Section 6.4.2. At a symmetric body at zero angle of attack it has a shape which resembles a slip-flow boundary-layer profile (see Fig. 9.26 on page 370), the symmetric case in Fig. 6.22. In the asymmetric case a wake-like entropy layer appears, at least around the lower symmetry plane [5]. In our cases this situation is given. Entropy-layer swallowing must be taken into account in boundary-layer computation schemes and it plays a role in laminar-turbulent transition.

Flow three-dimensionality Above we have noted the geometrical situation along the lower symmetry lines of the two vehicles. Hence boundary-layer flow three-dimensionality is present at the SS Orbiter in the nose region and in down-stream direction for $x/L \lessapprox 0.12$. At the SÄNGER LS the flow on purpose is two-dimensional at the lower side of the forebody (inlet onset flow [5]), Fig. 7.8.

Laminar-turbulent transition does not happen at the SS Orbiter at the considered trajectory point. The unit Reynolds number is much too low there, upper left part of Fig. 2.3. However, at deflected trim or control surfaces transition-like phenomena might appear. At the Orbiter striation heating was observed at the body flap, possibly due to Görtler instability, Sub-Section 8.2.8. Further down on the trajectory, where the unit Reynolds number becomes large, of course laminar-turbulent transition happens. At 45 km altitude it happens at the lower side already at about 30 per cent vehicle length, Fig. 3.3. At the other surface portions it will happen further down on the trajectory. Due to the TPS tile surface at the SS Orbiter lower side, transition there is roughness-dominated, Sub-Section 8.3.1.

At the SÄNGER LS laminar-turbulent transition in any case happens, due to the low flight altitude. The prediction of the shape and the location of the transition zone today still is not possible to the needed degree of accuracy. At the upper side of the forebody transition will occur further downstream than at the lower side. One of the reasons is that at the upper side the unit

Table 1.2. Characteristic features of the flow at the lower side of the Space Shuttle Orbiter and of the SÄNGER lower stage's forebody, each at a distinctive trajectory point.

Characteristic feature	SS Orbiter windward (lower) side ($L = 32.8$ m)	SÄNGER LS forebody lower side ($L = 55$ m)
Flight altitude H [km]	72	33
Flight Mach number M_∞	≈ 24	6.8
Angle of attack α	$\approx 40°$	$6°$
Vehicle surface	rough (TPS tiles)	smooth
Aerothermoelasticity	negligible	important
Atmospheric fluctuations	not important	important
Surface radiation cooling	yes	yes
Surface emissivity coefficient ϵ	0.85 (nominal)	0.85 (nominal)
High-temperature real-gas effects	strong	weak
Catalytic surface recombination	yes	no
Heat transfer by mass diffusion	yes	no
Low density effects	negligible	none
Entropy layer	wake-like	wake-like
Flow three-dimensionality	initially, then none	none
Laminar-turbulent transition	no	yes
Boundary-layer state	laminar	lam/turb
Boundary-layer edge Mach number M_e	$0 \leqq M_e \lessapprox 2.3$	$0 \leqq M_e \lessapprox 5.5$
Boundary-layer edge temp. T_e [K]	$\approx 9{,}000 \rightarrow \approx 6{,}500$	$\approx 2{,}000 \rightarrow \approx 350$
Wall temperature $T_w \lessapprox T_{ra}$ [K]	$\approx 1{,}800 \rightarrow \approx 1{,}000$	$\approx 1{,}600 \rightarrow \approx 1{,}000$
Boundary-layer temp. gradient $\partial T/\partial y$	large	medium/large
Boundary-layer density gradient $\partial \rho/\partial y$	large	medium/large
Thermal surface effects—viscous	negligible	large
Therm. surface effects—thermo-chemic.	large	negligible

Reynolds number is approximately only one third of that at the lower side. The lower side is a pre-compression surface for the inlets, whereas the upper side is more or less a free-stream surface.[7] The SÄNGER LS is an aircraft-like flight vehicle and definitely transition sensitive, Chapter 8.

Boundary-layer edge Mach number The windward side boundary layer at the SS Orbiter at large angle of attack initially is a subsonic, then a transonic, and finally a low supersonic, however, not ordinary boundary layer. During re-entry one has typically at maximum $M_e \approx 2.3$, and mostly $M_e \lessapprox 2$ [19]. This is in contrast to the boundary layer at the lower side of the SÄNGER LS. There a true hypersonic boundary layer exists with appreciably high edge Mach numbers.

Boundary-layer edge temperature The boundary-layer edge flow at the SS Orbiter is characterized by very large temperatures and hence high-temperature real-gas effects. The given boundary-layer edge temperature at the stagnation point is guessed to be approximately 9,000 K from Fig. 2.3. Assuming for the expansion to $M_e = 2{,}3$ an effective ratio of the specific heats $\gamma_{eff} = 1.14$, [20], we arrive at $T \approx 6{,}500$ K at the beginning of the boattailing.

At the SÄNGER LS 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, inlet ramps and trim and control surfaces [5]. Hence the boundary-layer edge temperatures are moderate to low and the rather mild high-temperature real-gas effects are essentially restricted to these configuration parts and to the boundary layers.

Wall temperature The radiation cooling of the vehicle surfaces is very effective. This holds in particular for the SS Orbiter due to the small unit Reynolds number at the large altitude, the large surface curvature radii at the stagnation-point region and the then more or less flat surface. The radiation cooling at the SÄNGER LS would reduce the surface temperature even down to approximately 500 K, if the boundary layer would remain laminar, Section 7.3. Actually laminar-turbulent transition occurs with a subsequent rise of the wall temperature level to about 1,000 K. At the vehicle's nose the contradictory demands of minimization of wave drag and wall temperature exist. The first demand asks for small nose radii and the latter for large ones. The reader is referred in this regard to, e.g., [5, 21]. We note also that the radiation-adiabatic temperature T_{ra} in general is a good approximation of the actual wall temperature T_w, Chapter 3.

Boundary-layer temperature and density gradients Due the rather low surface temperatures because of the radiation cooling, strong wall-normal temperature gradients are found at the SS Orbiter. At the SÄNGER LS medium gradients are present for laminar flow and large ones for turbulent flow. Note that the resulting heat fluxes in the gas at the wall q_{gw} are *not* the heat fluxes q_w which enter the surface of the TPS or the hot primary

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[7] A free-stream surface is a vehicle's surface which is not inclined against the free stream.

structure. In general we have $q_w \ll q_{gw}$ because of the large amount of heat q_{rad} radiated away from the surface, Chapter 3. Because at both flight vehicles the attached viscous flow to a good approximation is a first-order boundary-layer flow, the density gradients are inverse to the temperature gradients [22].

Thermal surface effects—viscous At the SS Orbiter viscous thermal surface effects, Section 1.4, are negligible except to a certain degree at the deflected trim and control surfaces as well as at the thrusters of the reaction control system [5]. This is in stark contrast to the SÄNGER LS, where viscous thermal surface effects are of utmost importance. In this regard a number of examples is given in several chapters and in particular in Chapter 10.

Thermal surface effects—thermo-chemical These effects concern mainly surface catalytic recombination at the SS Orbiter due to the very hot boundary layer and the resulting thermo-chemical non-equilibrium of the flow, see also Chapter 10.

1.3 The Tasks of Aerothermodynamics

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

1. Aerothermodynamic shape definition, which has to take into account the thermal state of the surface, Section 1.4, if it influences strongly via thermal-surface effects the drag of the vehicle (CAV, ARV), the inlet performance, and the performance of trim and control surfaces (all classes):
   a) Provision of the aerodynamic data set [7], enabling of flyability and controllability along the whole trajectory (all vehicle classes).
   b) Aerothermodynamic airframe/propulsion integration for in particular airbreathing (CAV), but also rocket propelled (RV, ARV) vehicles.
   c) Aerothermodynamic integration of reaction control systems (RV, ARV, AOTV).
   d) Aerothermodynamic upper stage integration and separation for TSTO space transportation systems.
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 on both external and internal surfaces/structures.
   c) Determination of the aerothermoelastic properties of the airframe.

3. Definition of the necessary and the permissible surface properties (external and internal flow paths), see also Section 1.4:
   a) The only but deciding "necessary" surface property is radiation emissivity in view of external surface-radiation cooling. It governs the thermal loads of structure and materials, but also the thermal-surface effects regarding viscous-flow and thermo-chemical phenomena.
   b) "Permissible" surface properties are surface irregularities like roughness, waviness, steps, gaps etc. in view of laminar-turbulent transition and turbulent boundary-layer flow. For CAV's and ARV's they must be "sub-critical" in order to avoid unwanted increments of viscous drag, and of the thermal state of the surface.[8]

      For RV's surface roughness can be an inherent matter of the layout of the thermal protection system. 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 catalycity, which should be as small as possible, in order to avoid unwanted increments of the thermal state of the surface, e.g., of the wall temperature. Usually the surface catalytic behavior, together with emissivity and anti-oxidation 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.

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[8] 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.

1.4 The Thermal State of the Surface and Thermal Surface Effects

The influence of, for instance, the Mach number or the Reynolds number on the appearance and kind of flow phenomena is well known and can be found everywhere in the text books. Mach number, Reynolds number and other "numbers" are similarity parameters, Chapter 4. Often overlooked is that the ratio 'wall temperature' to, for instance, 'free-stream temperature' (T_w/T_∞) is also a similarity parameter, Section 4.4. In the text books one finds in this regard, with a few exceptions, usually at most that the wall temperature influences the skin friction, often in combination with the Mach number, and for the adiabatic wall only [23].

The classical wind tunnel experiment regarding heat loads is made with a cold model wall, often with an uncontrolled surface temperature. The task of the experiment is to find the distribution of the Stanton number and nothing more. This is the Stanton-number concept: the heat flux in the wall q_w is specified basically by the—on the whole model surface in general constant—difference of the recovery temperature T_r and the wall temperature T_w.[9] The heat flux in the wall is equal to the heat flux in the gas at the wall: $q_w = q_{gw}$.

At the radiation cooled surface of an hypersonic flight vehicle the situation is different. The wall temperature T_w basically is due to the balance of three heat fluxes: the heat flux in the gas at the wall q_{gw}, Sub-Section 4.3.2, the radiation-cooling heat flux q_{rad}, Sub-Section 3.2.1, and the heat flux in the wall q_w, Section 3.1. Other heat fluxes may be of importance, too: surface-tangential heat fluxes, heat fluxes due to non-convex effects, and to shock-layer radiation. Because the different fluxes are functions of the location on the vehicle's surface, the resulting wall temperature is a function of the surface location, too.

For hypersonic flight vehicles the actual wall temperature T_w and the temperature gradient in the gas normal to the vehicle surface $\partial T/\partial n|_{gw}$ are of large importance. We call them together the "thermal state of the surface". This state influences not only thermal loads, but also viscous and thermo-chemical flow phenomena at and near the vehicle surface (external and internal flow paths). We call this influence "thermal surface effects". Both the concept of the thermal state of the surface and the concept of thermal surface effects are important topics of this book.

The influence of the Mach number, the Reynolds number and other similarity parameters on the flow can qualitatively be discussed by looking at the orders of magnitude of the numbers. Take for instance the Mach number, which indicates compressibility effects in the flow, page 92. For $M \ll 1$ we speak of incompressible flow, at $M \approx 1$ we have the transonic regime and so on. Similarly we can make an ordering of viscous transport phenomena by looking at the relative magnitude of the Reynolds number, page 92.

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[9] The heat flux is the heat transported through a unit area per unit time.

Regarding the thermal surface effects, the situation is complicated. A simple ordering of effects is not possible. The influence of the thermal state of the surface on viscous and thermo-chemical surface effects of course is additional to that of the basic parameters Mach number, Reynolds number, stream-wise and cross-wise pressure gradients, etc. In several of the following chapters we show and discuss some examples of viscous thermal surface effects. Eventually we devote Chapter 10 to a deeper discussion of further examples. Examples of thermo-chemical thermal surface effects cannot be considered in the frame of this book.

We define now the thermal state of the surface and the thermal surface effects in a formal manner.

The Thermal State of the Surface. Under the "thermal state of the surface" we understand the temperature of the gas at the surface (wall temperature), *and* the temperature gradient, respectively the heat flux, in it normal to the surface [24].[10] 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 RV's or CAV's and ARV's flying in the Earth atmosphere at speeds below approximately 8 km/s [14].

The thermal state of the surface thus is defined by

- 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, Sub-Section 4.3.2) are not present,
- the temperature gradient in the gas at the wall, $\partial T/\partial n|_{gw}$, in direction normal to the surface, 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.[11] The heat flux q_w is not equal to q_{gw}, if radiation cooling is present, Section 3.1.

Surface radiation cooling implies that T_w, $\partial T/\partial n|_{gw}$, q_{gw} and q_w are not constant over a vehicle's surface. Partly large gradients appear in downstream direction and also in lateral direction.

If one considers a RV, the thermal state of the surface concerns predominantly the structure and materials layout of the vehicle, and not so much its aerodynamic performance, except in some instances the performance of aerodynamic trim and control surfaces [5]. This is because the RV flies a "braking" mission, where the drag—wave drag, form drag, however negligible skin-friction drag—on purpose is large (blunt configuration, large angle of

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[10] This is the basic definition. A more general definition would include also the temperature gradients in tangential directions. Such situations can be found at vehicle noses, leading edges, inlet cowl lips, etc., see, e.g., [5, 21]. In non-convex situations and if shock layer radiation is present, the definition must be generalized further. For our discussions we can stick with the basic definition.

[11] In this book the direction normal to the wall usually is defined as y-coordinate.

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 [5, 21].

The situation is different for an (airbreathing) CAV (or ARV in the airbreathing propulsion mode), 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 1.2. This concerns the drag, the performance of trim and control surfaces, and the performance of elements of the (airbreathing) propulsion system (inlet, boundary-layer diverter duct, nozzle) [21, 5].

Thermal Surface Effects. This book puts emphasis on these facts by introducing the concept of "thermal-surface effects", which extends the classical "Stanton number" concept coming from the beginnings of high-speed flight. The Stanton number concept concerns mainly the classical thermal (heat) loads, which are of importance for the structure and materials concept of a vehicle. In contrast to that thermal-surface effects concern wall and near-wall viscous-flow and thermo-chemical phenomena, Fig. 1.4. This holds for both the external and the internal flow path of a flight vehicle.

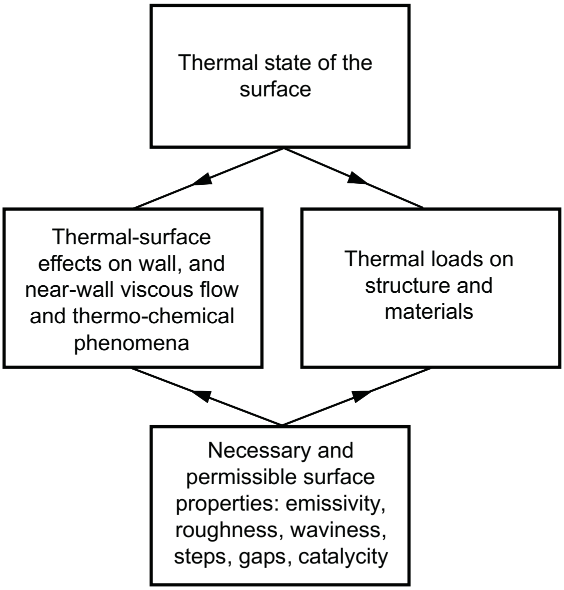

Fig. 1.4. The thermal state of the surface and its different aero-thermal design implications.

A good understanding of thermal-surface effects is deemed to be necessary in design work for hypersonic flight vehicles, in particular CAV's and ARV's. Thermal-surface effects regard both the external and the internal flow path. Special attention must be given to tests in ground-simulation facilities, where