9

The Thermal State of a Hypersonic Vehicle Surface

The thermal state of the hypersonic vehicle surface governs on the one hand thermal surface effects (these are the influence of wall-temperature and temperature gradient in the gas at the wall on viscous and thermo-chemical phenomena at and near the vehicle surface) and on the other hand the thermal loads on the vehicle surface (regarding the structure and material layout of a TPS or a hot primary structure), Fig. 9.1 [1]. The thermal state of the surface indirectly governs also mechanical (pressure and shear stress) loads via its influence on primarily the wall-shear stress, for instance, in erosion processes at a TPS. This is, of course, a typical viscous thermal surface effect.

The thermal state of the surface and hence both thermal surface effects and thermal loads are strongly influenced by the surface properties [1]. The most important property is a high surface emissivity in order to achieve sufficient (thermal) radiation cooling. Permissible properties are surface catalycity, sur-

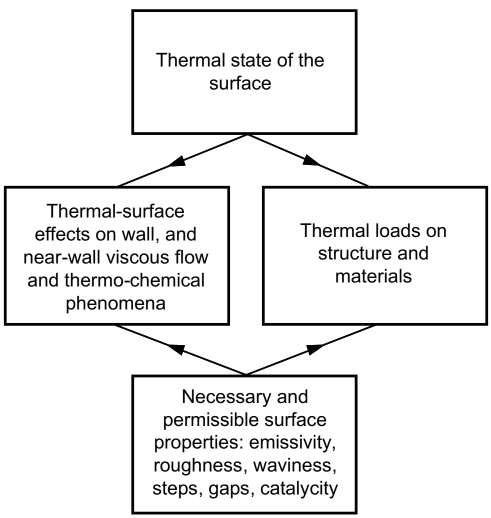

Fig. 9.1. The thermal state of the hypersonic vehicle surface and its different aerothermal design implications [1].

face roughness etc. These should be sub-critical, i.e., should have no detrimental influence on the near surface flow.

A particular problem is the determination of permissible surface roughness, waviness, step and gap height. The permissible geometrical scales should be as large as possible because a high surface quality would drive up manufacturing costs. On the other hand, it can be very problematic to model these surface characteristics in experimental and/or computational investigations. In this chapter we look first at the thermal situation at the surface of a hypersonic flight vehicle, define then the thermal state of the surface, and present finally an aerothermodynamic simulation compendium with special regard to the thermal state of the surface.

9.1 Heat Transport at a Vehicle Surface

Hypersonic flight vehicles either have a cold primary structure with a thermal protection system (typically RV-W's and RV-NW's) or a hot primary structure with internal insulation (such as some CAV's). In reality. mixtures of such structure and materials concepts are present. A RV-W, for instance, may have aerodynamic control surfaces with a hot primary structure without internal insulation.

A hypersonic vehicle surface typically is cooled by thermal surface radiation [1]. On surface portions and/or in flight speed/altitude domains where this is not sufficient, additionally active cooling, for instance by ablation (often employed on non-reusable flight systems) or transpiration cooling, is employed. For the following considerations we assume surfaces which do not change shape and no transpiration cooling. Active cooling can be allowed for by prescribing a heat flux q_w into the wall. Assuming a smooth surface[1] and reducing the situation to a one-dimensional one,[2] we find in the continuum regime the general thermal situation shown in Fig. 9.2.

Considering the situation shown in Fig. 9.2 in detail, we note [1]:

- The sum of all heat fluxes is zero:

$$q_{gw} + q_{rad,w,nc} + q_{rad,g} - q_{rad,w} - q_w = 0, \tag{9.1}$$

  and the wall temperature T_w is resulting from this balance. We assume $T_{gw} \equiv T_w$, neglecting a possible temperature jump in the slip-flow regime.

1 In general the surface must be sufficiently smooth only for airbreathing CAV's because they are drag critical, "permissible surface properties," see above and [1]. The classical TPS tile surface of the Space Shuttle Orbiter, for instance, has roughnesses which may be caused by tile misalignment, gaps, gap-filler protrusions etc. [2].

2 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. However, there might be situations, where this is not permitted, see Sub-Section 8.4.3.

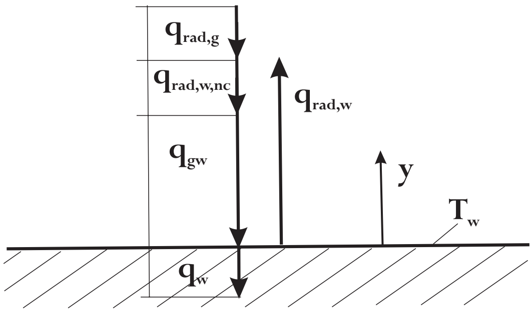

Fig. 9.2. Schematic description of the thermal state of the surface in the continuum regime, hence $T_{gw} \equiv T_w$. Tangential heat fluxes are neglected, y is the surface-normal coordinate, q_{gw}: heat flux in the gas at the wall, q_w: heat flux into the wall, $q_{rad,w}$: surface radiation (cooling) heat flux, $q_{rad,w,nc}$: surface radiation heat flux from non-convex surface portions, $q_{rad,g}$: shock-layer gas radiation heat flux.

- During hypersonic flight heat is transported to the vehicle surface by three physical processes:
  - Diffusive heat transport in the gas towards the wall, more precisely, the heat flux in the gas at the wall q_{gw} is the first.[3] In general, it consists of heat conduction, heat transfer due to mass diffusion in thermo-chemical non-equilibrium, but also of heat transfer due to slip-flow [1].
  - Transport of heat by thermal radiation from other surface portions of the flight vehicle $q_{rad,w,nc}$ due to non-convex effects is the second one. This transport happens, for instance, between the rear of a body flap and the fuselage (see Sections 6.3 and 6.4 for PHOENIX and X-38 examples), etc. It can be described with the help of a fictitious or effective emissivity coefficient ε_{eff} [1]. It takes into account the mutual visibility of the involved surface portions and especially the characteristic boundary layer thicknesses, which govern locally the wall radiation heat fluxes $q_{rad,w}$. Radiation heat coming from the sun can be neglected in our considerations.
  - Thermal radiation $q_{rad,g}$ of the vibrationally excited, dissociated and ionized gas in the shock layer is the third. For classical Low Earth Orbit (LEO) re-entry (RV-W's and RV-NW's) and also for CAV's with $v_\infty \lessapprox 8$ km/s at $H \lessapprox 100$ km, $q_{rad,g}$ usually can be neglected, because the diffusive heat transfer q_{gw} is dominant. But, for example, for Lunar return of a RV-NW with an entry speed of approximately 10.6 km/s, $q_{rad,g}$ becomes very important and approaches values of 50 per cent of the total heat flux towards the vehicle surface. This is due to the strong increase of ionized particles which are generated in the bow shock layer.

[3] In the literature this is usually called convective heating.

- Heat is transported away from the vehicle surface by two processes:[4]
  - Thermal radiation $q_{rad,w}$, which we usually denote in this book with q_{rad}, away from the surface for cooling purposes

$$q_{rad}(= q_{rad,w}) = \varepsilon\, \sigma\, T_w^4, \tag{9.2}$$

    with ε being the emissivity of the vehicle surface and σ the Stefan–Boltzmann constant, Section C.1.

    This is the major cooling mode for outer surfaces of low Earth Orbit re-entry vehicles and for airbreathing or rocket-propelled hypersonic flight vehicles with speeds below approximately 8 km/s, at altitudes below approximately 100 km. Note that at very low altitudes surface radiation cooling is not effective [1].
  - Heat transfer q_w into the surface material. This is the natural heat conduction process, which governs the thickness, for instance, of a TPS. In general $q_w \ll q_{rad,w}$. However, there are situations where this assumption is not valid. In the early stage of vehicle design processes (vehicle definition), it usually can be neglected. The resulting wall temperature T_w is then the radiation-adiabatic or radiation equilibrium temperature: $T_w \equiv T_{ra}$. In the vehicle development process the complete situation shown in Fig. 9.2 should be taken into account in order to arrive at precise thermal loads predictions. Looking at the potential of the modern numerical simulation methods, this becomes increasingly possible, Chapter 8. If active cooling by a heat exchanger below the surface is employed, q_w will anyway be large according to the cooling needs at that surface.

9.2 The Thermal State of a Vehicle Surface

Under the "thermal state of the surface," we understand the temperature of the gas at the surface, *and* the temperature gradient in it normal to the surface. As we have seen above, these are not necessarily those of and in the surface material. The thermal state of the surface thus is defined by [1]:

1. The actual temperature of the gas at the wall surface T_{gw} and the temperature of the wall T_w. If low-density effects (temperature jump) are not present, we have $T_{gw} \equiv T_w$, which we assume, for convenience, in the following considerations.
2. The temperature gradient in the gas at the wall $\partial T/\partial y|_{gw}$ 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.
3. The temperature gradient in the material at the wall surface $\partial T/\partial y|_w$ 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, Fig. 9.2.

[4] We do not consider here heat transport away from the surface due to ablation, transpiration, etc.

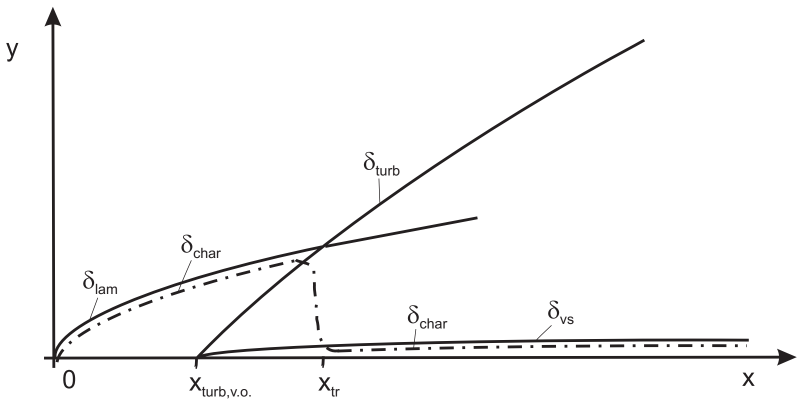

Fig. 9.3. Characteristic thickness δ_{char} regarding the heat flux in the gas at the wall and the wall shear stress of attached viscous flow of boundary layer type. In the laminar flow domain, the boundary layer thickness δ_{lam}, usually defined by the approach of 99 per cent of u_e, is the characteristic thickness. In the turbulent domain, it is the thickness of the viscous sub-layer δ_{vs} not the thickness δ_{turb}. The location of the virtual origin of the turbulent boundary layer, Sub-Section 10.4.4, is denoted with $x_{turb,\,v.o.}$, the transition location with x_{tr}.

We do not discuss here the implications of the thermal state of the surface for hypersonic flight vehicles of all kinds. The reader instead is referred to [1]. We note, however, that in general $\partial T/\partial y|_{gw}$ or q_{gw} and T_{ra} decrease strongly for laminar flow from the front part of a hypersonic vehicle towards its aft part. The reason is that the characteristic thickness of a laminar boundary layer δ_{lam} increases with the boundary layer running length x, Sub-Section 10.4.2: $\delta_{lam} \sim x^{0.5} \Rightarrow q_{gw,lam} \sim x^{-0.5}$, $T_{w,lam} \approx T_{ra,lam} \sim x^{-0.125}$.

If the boundary layer is turbulent the effect is not so pronounced because the characteristic thickness regarding the heat flux in the gas at the wall and the wall shear stress is the thickness of the viscous sub-layer δ_{vs}, which increases more slowly with the boundary layer running length x:[5] $\delta_{vs} \sim x^{0.2} \Rightarrow q_{gw,turb} \sim x^{-0.2}$, $T_{w,turb} \approx T_{ra,turb} \sim x^{-0.05}$ [1]. These and the above relations are of qualitative nature, but approximate reality to a good degree, if they are applied in the main flow direction, with flow three-dimensionality and high temperature real gas effects being small.

The different characteristic thicknesses of laminar and turbulent boundary layers, Fig. 9.3, must be taken into account in grid generation for numerical methods. A special problem arises for the turbulent boundary layer. The characteristic thickness of turbulent flow is that of the viscous sub-layer δ_{vs} [1], which is much smaller than the boundary layer thickness δ_{turb}.

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[5] Actually the proportionality $x^{0.2}$ is that of the scaling thickness δ_{sc} discussed in [1]; more correctly $\delta_{vs} \sim x^{0.1}$.

It is expressed in terms of the non-dimensional wall distance y^+ [3, 4]:

$$y^+ = \frac{y \rho u_\tau}{\mu}, \tag{9.3}$$

with the friction velocity

$$u_\tau = \sqrt{\frac{\tau_w}{\rho_w}}. \tag{9.4}$$

With $y^+ \approx 5$ defining the thickness of the viscous sub-layer,[6] the first grid line away from the surface usually is located at $y^+ \lessapprox 1$. Because the velocity profile is linear in that regime, it is sufficient to put two to three grid lines below $y^+ \approx 5$. The above holds, if the transport equations of turbulence are integrated down to the body surface, which is the case with the so-called low-Reynolds number formulations. If a law-of-the-wall formulation is used, the first grid line can be located at $y^+ \approx 50$–100 and the distance down to the wall is bridged with the law-of-the-wall.

However, for both formulations, one must keep in mind that with radiation cooled surfaces, large surface-normal gradients and near-wall extrema of the temperature T or the internal energy e occur [1]. If the attached viscous flow is of boundary layer type, then the density ρ accordingly has a large surface-normal gradient and a wall-near extremum, too. This must be taken into account when defining the computation grid.

We note further that the thermal state of the surface in general plays an important role for (airbreathing) CAV's, which like any aircraft are drag-sensitive. There, all viscous phenomena are affected even very strongly by the thermal state of the surface (viscous thermal surface effects).

If one considers RV-W's and RV-NW's, the thermal state of the surface concerns predominantly the structure and materials layout of the vehicle (thermo-chemical thermal surface effects with regard to thermal loads), and not so much its aerodynamic performance. This is because the RV flies a "braking" mission where the drag is on purpose large (blunt configuration, high angle of attack). Of course, if a flight mission demands large down-range or cross-range capabilities in the atmosphere, this may change.

9.3 Aerothermodynamic Simulation Compendium

The following compendium lists aerothermodynamic simulation means; for principal simulation topics see [1]. We list here the general capabilities of simulation means with special regard to the simulation of the thermal state of a vehicle surface in view of thermal loads and thermal surface effects. Especially regarding the computational simulation, it is recommended to look at overviews and reviews, e.g., [5]–[10]. However, the discrete numerical methods of aerodynamics and aerothermodynamics have made large progress since

6 See [1] for the explicit relation for δ_{vs}.

these papers and books were written. This also holds for experimental simulation, especially with non-intrusive measurement methods.

9.3.1 Ground-Facility Simulation

- Facilities
  - **"Cold" facilities:** Blow-down and continuous facilities, total temperatures from ambient up to approximately 1,500 K. Limitations: Restricted similarity-parameter reproduction (usually only true Mach number), cold model surfaces.
  - **"Hot" (high-enthalpy) facilities:** Pulse facilities (shock tunnels of all kind), plasma tunnels (usually for materials and structure tests). Limitations: In general restricted similarity-parameter reproduction, high-enthalpy similarity usually means a flight-velocity but not a flight Mach number similarity (Mach number independence necessary), thermo-chemical freezing effects during nozzle expansion, cold model surfaces.

- Use for hypersonic flight vehicle definition and development
  - **Applications:** Aerodynamic shape definition, design verification, data set generation.
  - **Results:** Forces and moments. Discrete surface points measurements: Pressure p_w, shear stress τ_w, temperature T_w, heat flux q_w. Because radiation cooling cannot be simulated in ground-simulation facilities, this means $q_w \equiv q_{gw}$. Distributed surface data (image-based measurement techniques): Pressure p_w (pressure sensitive paint), shear-stress τ_w (skin-friction) lines (oil-film pattern), temperature T_w and heat flux q_w (temperature sensitive paint). Off-surface flow visualization (schlieren, shadowgraph, interferometry): Shock locations, separation structures, wakes. A hot experimental technique in general is not available for ground facility simulation, although it is in use for in-flight testing.

    We note that many of those techniques are not well developed if applicable at all for hypersonic facilities, whether long or short duration facilities. For instance, short duration tests may not allow enough time for the paints to react. Not all of the surface techniques may be applicable in hot facilities. Also in-flight testing in general makes not use of optical and non-intrusive techniques.

    Complete vehicle models due to their rather small size usually do not allow the reproduction of realistic surface properties (irregularities, waviness, steps, gaps, etc.), which may influence the near-surface flow.[7] For the Space Shuttle Orbiter, however, tile gap patterns have been reproduced on the model surface for transition measurements [2].

[7] The influence of such properties in general is simulated and studied with the help of dedicated generic models.

– **Thermal state of the surface:** Temperature T_w and heat flux into the wall q_w (usually indirectly found) can be measured. For perfect gas or gas in thermo-chemical equilibrium, the gradient $\partial T/\partial n|_{gw}$ can be determined. All such determinations, however, as a rule, applies only for cold models. Hot-spot and cold-spot situations can only be detected with surface-mapping techniques if resolution is adequately high. As a rule, the true flight situation cannot be simulated, neither in cold nor in hot facilities: Cold model surfaces, no simulation of surface radiation cooling, restricted similarity-parameter reproduction (usually only true Mach number). If turbulent flow is present on parts of the vehicle surface in reality: True laminar–turbulent transition simulation is not possible since turbulence tripping is problematic.

Summary: With the present capabilities, thermal loads can be measured with acceptable accuracy and reliability but will be problematic for meeting meet future higher demands. The true in-flight thermal state of the surface and hence thermal surface effects cannot be simulated. "Hot model" techniques have been tried, but in general are not established.´

9.3.2 Computational Simulation

- Numerical methods
  - ☐ Computer codes (steady state and time-accurate solutions)
    - **Equations:** Viscous shock-layer equations (laminar), Euler equations, coupled Euler/higher-order boundary layer equations (laminar and turbulent), full Navier–Stokes equations (laminar and turbulent (Reynolds/Favre-averaged Navier–Stokes equations (RANS)), for simulation problems in non-continuum flow regimes the Boltzmann equation (Monte-Carlo methods).
    - **Flow-physics models:** Laminar-flow transport properties (with some exceptions good quality), statistical turbulence models are acceptable, except for strong interaction phenomena (turbulent shock/boundary layer interaction, separation, corner flow, et cetera), criteria for laminar–turbulent transition are neither accurate nor reliable.
    - **High temperature real gas models:** Thermal and chemical equilibrium, thermal nonequilibrium, chemical nonequilibrium. Gas models with different numbers of species and reactions, including ionization, multi-temperature models with different numbers of vibration temperatures are available. All models have, with some exceptions, good quality (problem of accumulated inaccuracies?).
    - **Type of surface boundary conditions (viscous codes):** No-slip boundary conditions in the continuum regime, wall (and shock) slip effects in the rarefied gas regime $H \approx$ 80–100 km; prescribed wall temperature or heat flux including adiabatic wall, radiation-adiabatic wall

(in multidisciplinary methods coupling with heat flux into the wall); non-catalytic, finite-rate catalytic, and fully catalytic wall; ablation pyrolysis, gas-mass flux, surface degradation.

The codes, as a rule, are applied to rigid flight-vehicle configurations, new multidisciplinary methods permit to take into account deforming and movable surfaces, i.e., aerodynamic trim and control surfaces, etc.

☐ Use for hypersonic flight vehicle definition and development

- **Applications:** Aerodynamic shape definition, design verification, data set generation, problem diagnosis.
- **Results:** Forces and moments, surface and off-surface distributions of pressure, shear-stress, temperature(s), heat fluxes, gas species, velocity components, shock locations, entropy-layer phenomena, etc. Only with Navier-Stokes methods: strong interaction flows including hypersonic viscous interaction, low-density (slip flow) effects, flow separation, wakes. Flow topologies of all kind, as well as hot-spot and cold-spot situations can be identified.

  Not possible in general is the simulation of real-life surface properties (irregularities, waviness, steps, gaps, et cetera) in view of laminar-turbulent transition and turbulent flow. If a sensitivity exists with regard to laminar-turbulent transition, the situation becomes critical. Results of computations of separated turbulent flow in general are not reliable.
- **Thermal state of the surface:** The complete thermal state of the surface, i. e. the true flight situation, can be computed, including non-convex effects $q_{rad,w,nc}$ and shock-layer gas radiation $q_{rad,g}$. In multidisciplinary simulations heat transport into the wall q_w can be added. Hot-spot and cold-spot situations can be detected. Limitations are due to the insufficient modelling of laminar-turbulent transition and turbulent separation.

Summary: With the present capabilities viscous and thermo-chemical thermal surface effects as well as thermal loads can be computed with good accuracy and reliability, as long as no large sensitivity is given regarding laminar–turbulent transition and turbulent separation.

• Approximate (engineering) methods

☐ Computation Methods

- **Type:** a) Inviscid methods: Newton-type, shock-expansion type, etc., b) viscous methods (laminar and turbulent): stagnation point relations (laminar), relations for flat surface portions (hypersonic viscous interaction can be taken into account in some methods), swept cylinders (attachment lines) etc. [11], simple (2-D, axisymmetric analogue) boundary layer methods (finite difference and integral methods).
- **Flow-physics models:** Capabilities and restrictions like for numerical methods.

– **High temperature real gas models:** Capabilities and restrictions like for numerical methods. In general rather simple models are employed.
– **Type of surface boundary conditions (viscous methods):** In general only no-slip boundary conditions; prescribed wall temperature or heat flux including adiabatic and radiation-adiabatic walls.

☐ Use for hypersonic flight vehicle definition and development
– **Applications:** Aerodynamic shape definition, data set generation, trajectory definition and optimization.
– **Results:** Forces and moments, 1-D and quasi-2-D surface distributions of pressure, shear-stress, temperature, heat fluxes. Flow topologies of all kind, as well as hot-spot and cold-spot situations cannot be identified. If a sensitivity exists with regard to laminar–turbulent transition, the situation again becomes critical. The boundary layer methods permit to indicate flow separation.
– **Thermal state of the surface:** In principle the complete thermal state of the surface, although for simple surface configurations, can be computed, including non-convex effects $q_{rad,w,nc}$ and shock-layer gas radiation $q_{rad,g}$. In general, however, engineering methods do not have these capabilities. In simple multidisciplinary simulations heat transport into the wall q_w can be added. Hot-spot and cold-spot situations cannot be detected. Limitations again are due to the insufficient modelling of laminar-turbulent transition and turbulent separation.

Summary: Thermal loads can be computed for simple surface configurations with attached viscous flow, as long as no large sensitivity is given regarding laminar-turbulent transition. The description of viscous and thermo-chemical thermal surface effects in general is restricted, although in principle possible to a certain degree.

9.3.3 In-Flight Simulation

- **Capabilities:** In discrete surface points measurement of wall pressure, wall temperature, heat flux into the wall q_w, etc. are feasible with acceptable results. Avoided must be a local falsification of the actual vehicle surface properties (in terms of radiation emissivity and catalycity) by the material and surface properties of the inserted gauges and, in addition, their possible pollution.

  In-flight distributed wall-temperature and other measurements are not feasible in general. Initial wall-temperature mappings have been performed on the Space Shuttle Orbiter's windward side surface by means of infrared imagery from the Kuiper Astronomical Observatory aircraft [12]. The project was rated a limited success. Space Shuttle Orbiter leeside infrared temperature imagery was performed with the help of a pod mounted atop the vertical fin of the vehicle [13]. This obviously more successful experiment was performed during five missions.

A special topic of in-flight simulation is parameter or systems identification, i.e., the determination of the true aerothermodynamic performance and properties of the real, elastic, controlled flying vehicle. The most completely studied vehicle in this regard is the Space Shuttle Orbiter, with a host of data available in [14].

An important prerequisite for all kind of in-flight measurements is an accurate air-data system, because the measured data must be correlated with the flight speed and the attitude of the vehicle, as well as with the thermodynamic data of the atmosphere ahead of the vehicle. Good accuracy is attained for the velocity v_∞, the pressure p_∞, and the attitude. A special problem in this regard is the atmospheric density ρ_∞. Opto-electronic/spectroscopic measurement systems should be able in the future to provide highly accurate measurements of ρ_∞ and T_∞.

- **Applications:** Acquisition of aerothermodynamic data for code modelling and validation, laminar-turbulent transition data, etc. Tests of heat-protection systems including flexible external insulations (FEI), hot structures, ablators, surface degradation, etc.
- **Thermal state of the surface:** The thermal state of the surface can be determined, if the emission and catalytic properties of the surface (possible falsification problem due to sensor material) are known. If that is the case, thermal surface effects can be identified by data analysis with the help of numerical aerothermodynamic computation methods.

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