University of Stuttgart, Aerospace Engineering and Geodesy Dept. - Lecture -

Hypersonic flow and flight

Master Level, Specialization 4 lecture hours per week in WS, 3-6 LPs/ECTS

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Hypersonic Flow

NASP Study (USA, 1986)





Shuttle (USA, 1981)



When which body shape and why?

Sänger-Studie (GER) 1963/88

MSc. course - Institute for Aerodynamics and Gas Dynamics

X-43 (USA, 2005)

Dryden Flight Research Center ED98-44824-1 per -X aircraft. NASA/Dryden Illustration by Steve Lighthi



Contents (1)

0	Motivation, own research work (transition, film cooling)
Ι	Inviscid Hypersonic Flow
I.1	Velociy-altitude map
I.2	Shock relations, Tsien's similarity parameter
I.3	Expansion wave relations
I.4	Waverider principle
I.5	Dynamic pressure, total pressure, pressure coefficient, total-pressure loss:
	definitions and flow-physical meaning in hypersonics
I.6	Methods to gain c_p based on local surface inclination
I.6.1	Newtonian theory
I.6.2	Modified Newtonian theory: inclined plate, sphere
I.6.3	Methods for sharp bodies only: tangent wedge/cone, shock-expansion
I.7	Mach-number independence and similarity for slender bodies
I.8	Small-disturbance-theory application: pointed slender circular cone
I.9	Conical flow: pointed circular cone, Taylor-Maccoll equation,
	3D effects, elliptic cone
I.10	Fundamental aspects of flow-field computations - shock fitting/capturing
I.10.1	Space-marching techniques, subsonics problem
I.10.2	Time-marching: steady/unsteady flow



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- I.11 Shock standoff distance
- I.12 Aspects of inviscid/viscous CFD results and the Hyper-X(-43) project

II Viscous Hypersonic Flow

- II.1 Boundary layers: Navier-Stokes equations and friction terms, parabolized equations volumetric viscosity / second viscosity / thermal relaxation experimental simulation: problems of kinematical inversion
- II.1.1 Laminar boundary layers and boundary-layer equations
- II.1.2 Self-similar solutions

II.1.2.1	Flat plate
	velocity /temperature profile, recovery-temperature,
	friction /heat coefficient (stanton number), Reynolds analogy
II.1.2.2	Pointed circular cone
II.1.2.3	Stagnation flow: inkompressible case revisited;
	body shape and boundary-layer state: wall heating
II.1.3	Turbulent boundary layers
II.1.3.1	Flat plate: velocity profiles, scaling (van Driest)
	recovery temperature, wall heating

II.1.3.2 Pointed circular cone



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II 1 4	The reference-temperature concept
II.2	Laminar-Turbulent Transition
II.2.1	Fundamental scenarios: regular bypass transient growth: recentivity
II.2.1 II.2.2	Linear Stability Theory:
	disturbance amplification, Mach number influence, vorticity (1 st) mode
	and acoustic (2 nd) mode, supersonic disturbance
II.2.3	Transition Prediction:
	e-to-the-N method (smooth wall); simplified methods (rough wall)
II.2.4	wall-cooling, radiation adiabatic wall (radiative equilibrium)
II.2.5	Effects of other parameters
II.3	Viscous Interaction (boundary-layer/external flow)
II.3.1	pressure interaction near leading edge
II.3.2	shock/boundary-layer interaction, front spike

III High-Temperature Effects

- III.1gas models: vibrational excitation, dissociation;
related velocity-altitude map for earth atmosphere
- III.2Thermochemical States:
equilibrium, frozen flow, non-equilibrium, Damköhler number,



Contents (4)

III.2.1	Inviscid flow in equilibrium
	thermodynamics: molecules ' degrees of freedom
	chemistry: dissociation-/recombination reactions
	speed of sound = f (temperature, pressure)
III.2.1.1	Normal shock: reduction of temperature rise
III.2.1.2	Blunt body: reduction of shock stand-off distance
III.2.1.3	Oblique shock: <i>larger maximum deflection angle</i>
III.2.1.4	Nozzle flow: temperature rise by reombinations
III.2.2	Inviscid flow in non-equilibrium
III.2.2.1	Nozzle flow: <i>thermochemically, thermally frozen</i>
III.2.2.2	Normal shock: route from frozen state to equilibrium
III.2.2.3	Blunt body: regions of iso-thermochemical states
III.2.3	Viscous flow: <i>diffusion</i> ; wall heat flux dependent on wall catalycity
III.2.3.1	Stagnation flow: boundary-layer profiles and wall heat flux
	= f (reaction rates in the boundary layer with binary gas)
III.3	Aspects of the SHEFEX project (facetted forebody nose)



Basic literature

[1] John D. Anderson Jr.: *Hypersonic and High-Temperature Gas Dynamics*. AIAA, 2006, 2nd edition (McGraw-Hill, 1989), ISBN 1-56347-780-7 (ca. € 95) [2] Ernst H. Hirschel: *Basics of Aerothermodynamics*. Springer, 2004, ISBN 3-540-22132-8 (ca. € 65/95) [3] Johann T. Heynatz: Hyperschallströmungen – Grundlagen und Hinweise. Verlag Dieter Thomas, 1997, ISBN 3-931776-11-5 (ca. € 34) [4] John D. Anderson Jr.: *Modern Compressible Flow*. McGraw-Hill, 3rd ed. 2004, ISBN 978-0071241366 (€ 60-220). [5] Maurice Rasmussen: *Hypersonic Flow*. Wiley Interscience, 1994, ISBN 0-471-51102-1 (€ 185) [6] Frank M. White: *Viscous Fluid Flow*. McGraw-Hill, 3rd ed. 2005, ISBN 978-0071244930 (€ 60-220) [7] Hermann Schlichting, Klaus Gersten: Boundary-Layer Theory. Springer, 8th ed. 2003, ISBN 3-540-66270-7 (or: previous eds. McGraw-Hill)



Newtonian Theory for inviscid c_p , c_D , c_L

Hypersonic Flow



Fig. Drag coefficient for a sphere and cylinder with conical forebody as a function of Mach number (symbols: flight experiments) [1]. Mach number independence starts earlier for blunt bodies because of larger shock angles. c_D (sphere, $M_{\infty}=0$) is for $10^3 \le Re_D \le 10^5$ (laminar separation).



Laminar-turbulent Transition (5)

Hypersonic Flow



Fig. Temperature along laminar-turbulent transition

a) pointed circular cone with flare, M=6, $R_{nose}=2.5\mu m$ [Horvath et. al, RTO-RSM-AVT-111, Prag, 2004]. b) symmetry line for Sänger lower stage, $Re_{unit}=1.5\cdot10^6/m$, $L_V=55m$, M=6.8, $\alpha=6^\circ$ at adiabatic ($\varepsilon=0$) and radiation-adiabatic (cooled, $\varepsilon=0.85$) wall; steady CFD with transition position fixed [2]). With radiative equilibrium the temperature increase is strong. During transition the turbulent value is often surpassed.



Viscous interaction (1)

Hypersonic Flow





Fig. a Effect of an aerospike.

1 – front shock by spike, 2 – recirculation region, 3 – separation shock, 4 – re-attachment shock. Density, Mach 7, thesis by Gauer, HyShot-IAG, 2006 (2-d axisymmetric CFD).



Viscous interaction (2)

Hypersonic Flow



Fig. b Aerospike with L/D=2, D/d=4, density- and axial velocity at M=7. L – spike length, D – nose diameter of main body, d – of forebody; drag reduction: 46%.



Viscous interaction (3)

Hypersonic Flow



Fig. c Like fig. b, temperature distribution (upper) and u-isolines in the recirculation region (lower); middle: perspective view.

