Hypersonic Transition in High Enthalpy Facilities

Dr. Alexander Wagner
Institute of Aerodynamics and Flow Technology
Spacecraft Department
German Aerospace Center (DLR)
Bunsenstrae 10
Göttingen, 37073
Germany

Alexander.Wagner@dlr.de

ABSTRACT

The present manuscript supports a lecture given in the scope of the VKI Lecture Series 'Multiphysics phenomena analysis on boundary layer stability in hypersonic regime'. It is limited to hypersonic transition phenomena in hypersonic shock tunnels at low enthalpy conditions. The manuscript provides a brief overview over existing high enthalpy shock tunnels and discusses the role of such facilities with respect to hypersonic boundary layer transition research. The operating principle of a typical shock tunnel is explained based on the High Enthalpy Shock Tunnel Göttingen (HEG). Furthermore, techniques to assess the free-stream disturbances in the challenging test environment of a shock tunnels are discussed and results obtained by means of a wedge shaped probe a presented. Moreover, transition studies on the second mode instability in HEG are introduced. The presence of the second mode and its dominance in the transition process on a cone allows to study transition control strategies targeting the suppression of the second mode. A passive control strategy applying ultrasonically absorptive carbon matrix composites led to promising results and encourages the development of the next generation of, high temperature resistant, porous ceramics.

Contents

1.0 INTRODUCTION

Hypersonic boundary layer transition is a crucial design parameter for hypersonic vehicles. Despite the fact that transition has been an area of intense research over the past decades, the transition process is still not completely understood.[1] Transition to turbulence affects the design of a hypersonic vehicle primarily through an increase of aerodynamic heating and increased skin friction drag. Furthermore, it also effects pressure drag, aerodynamic control efficiency and engine performance. The Defence Science Board which evaluated the U.S. National Aerospace Plane Program (NASP) in 1988 formulated the following remarkable statement on the implication of an unknown transition location:[2] "The degree of uncertainty significantly affects the ... estimates of engine performance, structural heating and drag. The assumption made for the point of transition can affect the design vehicle gross take off weight by a factor of two or more". Beyond the prediction of the transition location, the increase of the laminar portion of the boundary layer is of critical importance to the design and optimization of these vehicles.[3] This ultimately motivates the development of concepts to control hypersonic transition. Among a number of concepts studied in the research community passive transition control by means of ultrasonically absorptive surfaces were found to be promising.[4, 5] This is particularly true if the absorptive surface properties can be combined with thermal protection capabilities.[6]

As part of the transition studies a broad effort was taken over the last few years to characterize free-stream disturbances in hypersonic wind tunnels by applying different techniques such as hot wire anemometry, pitot probes and focused laser differential interferometry. In particular hot wires and pitot probes are common standard techniques but unfortunately not applicable in shock tunnels. Therefore, a wedge-shaped probe was designed to measure free-stream disturbances over a wide frequency range in hypersonic wind tunnels and in particular in hypersonic shock tunnels with harsh test environments. It follows the same principle of using a slender probe instead of a blunt geometry to avoid strong shocks and thus the complexity of a subsonic flow field associated with complex amplification of the tunnel disturbances.[7, 8] The probe was successfully used in three hypersonic wind tunnels, the DLR High Enthalpy Shock Tunnel Göttingen (HEG), the DNW Ludwieg tube (RWG) and the TU Braunschweig Ludwieg tube (HLB), covering Mach 3, 6 and 7.4 as reported in Wagner et al. [9]. The experimental efforts are accompanied by DNS computations conducted by Cerminara et al. [10, 11].

2.0 HYPERSONIC HIGH ENTHALPY WIND TUNNELS

Hypersonic high enthalpy flows are usually generated by means of shock tunnels to realise the required total temperatures and pressures. Despite the short test times and the harsh test environment found in high enthalpy shock tunnels, numerous studies on hypersonic boundary layer transition were conducted in those facilities over the past years. Shock tunnels are of particular value if flight conditions for instance for scramjet studies need to be realized or real gas effects are studied.

Without any claim to completeness, transition studies were conducted for instance in the following shock tunnels around the world:

- T4 of the University of Queensland, Australia [12–14]
- T5 of the California Institute of Technology, USA [5, 15–17]
- LENS facilities at Calspan-University at Buffalo Research Center, USA [18–21]
- HIEST shock tunnel at JAXA, Japan [22–24]

- Longshot at the von Karman Institute, Belgium [25, 26]
- High Enthalpy Shock Tunnel Göttingen (HEG), Germany [27–31].

In the following section the High Enthalpy Shock Tunnel Göttingen (HEG) and its operating principle will be introduced in more detail as a representative free-piston driven reflected shock tunnel.

2.1 The High Enthalpy Shock Tunnel Göttingen (HEG)

The High Enthalpy Shock Tunnel Göttingen (HEG) is a free-piston driven reflected shock tunnel providing a pulse of gas to a hypersonic nozzle at stagnation pressures of up to $200\ \mathrm{MPa}$ and stagnation enthalpies of up to $25\ \mathrm{MJ/kg}$.[32–35] The overall length and mass of the facility is $60\ \mathrm{m}$ and $250\ \mathrm{t}$, respectively. As depicted in figure 1 the tunnel consists of three main sections. The driver section consists of a secondary reservoir which can be pressurized up to $23\ \mathrm{MPa}$ and a $33\ \mathrm{m}$ long compression tube. The adjoining shock tube (or driven tube) has a length of $17\ \mathrm{m}$. The end of the tube is equipped with a sleeve to allows tests at high enthalpy.[36] The shock tube is separated from the compression tube by a $3-18\ \mathrm{mm}$ stainless steel main diaphragm. The third section is separated by a thin Mylar® diaphragm and consists of the Laval nozzle, the test section and the dump tank. HEG was designed to investigate hypersonic flows with high enthalpies. To obtain such enthalpies, high shock speeds are required in the shock tube which is realized by generating a driver gas with a high speed of sound. This is achieved through a combination of light driver gas and a high driver gas temperature. Various techniques have been developed to generate such driver gas conditions, e.g. heating through electrical resistance, arc heating, combustion drivers or shock heated drivers. However, these techniques have a number

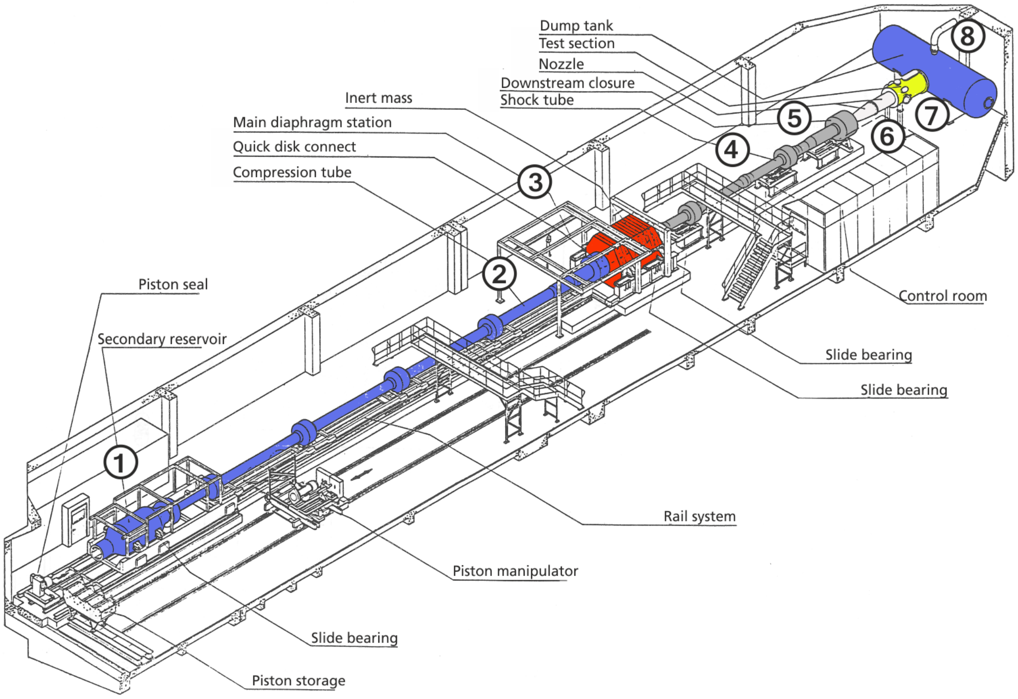

Figure 1: Schematic view of the High Enthalpy Shock Tunnel Göttingen (HEG), Martinez Schramm [37].

of disadvantages such as difficult design constraints due to for instance high heating loads, [38, 39], or the presence of heavy combustion products in the driver gas. The latter reduces the driver speed of sound which is in contrast to the necessity of high gas temperatures.[40] To bypass these problems the free-piston compression process, which allows high volumetric compression ratios without the previously mentioned disadvantages, was developed by Stalker [41–43].

The operating principle of a shock tunnel using a free-piston to compress the driver gas is the following. At the beginning of a test in HEG the piston is at the upstream end of the compression tube, see position 1 in figure 1. The compression tube, position 2, is filled with a driver gas (typically a helium/argon mixture) at low pressure and ambient temperature. While the pressure in the secondary reservoir is increased the piston is kept in place. Once the required pressure to drive the piston is reached it is released. At this point the energy of the expanding gas in the secondary reservoir accelerates the piston down the compression tube. By the time the pressure behind the piston is equal to the pressure in front, the piston has sufficient kinetic energy to continue the compression process due to the piston inertia. Its kinetic energy is then transferred to the driver gas which is adiabatically compressed until the downstream main diaphragm ruptures, position 3, and the shock-tube flow is initiated. To obtain a reproducible diaphragms rupture process the diaphragms are cross-scratched. Diaphragms of different thickness are used to realize different burst pressures. To ensure constant nozzle reservoir conditions, in the order of few milliseconds, the conditions in the driver gas must be held constant for a similar time period. Therefore, the main diaphragm is allowed to rupture before the compression process is completed and the piston comes to rest. The piston trajectory is tuned such that after diaphragm rupture the volume displaced by the piston matches the mass flow into the shock tube, position 4. Thereby, the loss of driver gas due to the expansion into the shock tube is compensated and the driver pressure remains constant for a small holding time. Further, expansion waves reflected at the compression tube end wall should be reduced or cancelled. At the downstream end of the shock tube a thin secondary diaphragm is used to separate the shock tube containing the test gas from the downstream part of the tunnel which is kept under vacuum conditions. After the main diaphragm rupture a primary shock wave travels along the shock tube. The shock wave is reflected at

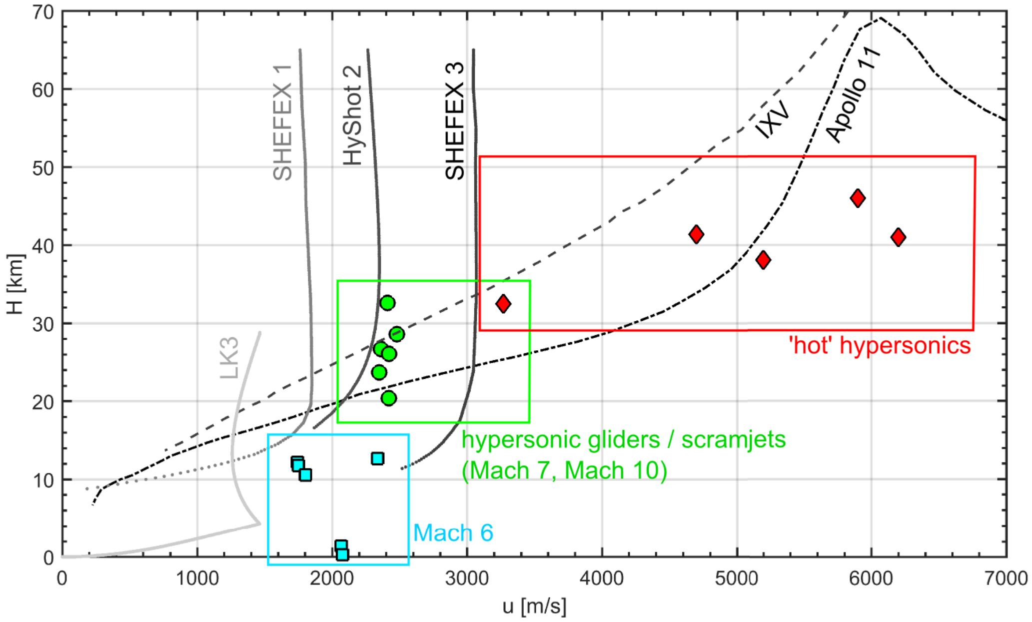

Figure 2: Subset of the HEG test conditions.

the shock tube end wall and ruptures the secondary diaphragm mounted close to the nozzle throat, position 5. The reflected shock leaves a region of almost stationary high temperature test gas in the nozzle reservoir which subsequently expands through the convergent-divergent hypersonic nozzle, position 6, into the test section, position 7, and the dump tank, position 8.

Figure 2 shows a subset of the HEG test conditions which are realized by the above described operating principle. The test conditions are presented in an altitude over velocity coordinate system to indicate the achieved velocities typical for high enthalpy shock tunnels. Furthermore, the figure contains information on the different Mach number ranges and test windows for instance of interest with regard to hypersonic glider and scramjet studies.

3.0 FREE-STREAM DISTURBANCES IN SHOCK TUNNELS

Free-stream disturbances play an important role in the boundary layer transition process since the breakdown mechanisms are initial condition dependent. The process through which free-stream disturbances such as vorticity, sound, entropy inhomogeneity as well as microscale and macroscale particulates, enter the boundary layer as unsteady fluctuations of the basic state is called receptivity.[44] Since the majority of the transition studies are conducted in noisy facilities and existing quiet tunnels cannot cover the full range of hypersonic flows it is important to characterize the free-stream disturbances.

A number of experimental techniques are commonly used for this purpose. For instance hot wire anemometry (HWA) is widely used to quantify disturbances radiated from a supersonic turbulent boundary layer or to determine the source and the nature of the disturbances.[45, 46] Recently, Masutti et al. [47] characterized the disturbance level of the Mach 6 blow-down facility H3 at VKI. Unfortunately, the technique is not applicable to shock tunnels. Due to the limited bandwidth, approximately $100\ \mathrm{kHz}$, the high frequency content in such flows cannot be assessed. Furthermore, the total temperatures in such facilities are very high compared to blow-down or Ludwieg tube facilities which thwarts the data reduction strategy introduced by Smits et al. [48]. Furthermore, the harsh test environment and the impulsive nature of the flow most likely compromise the delicate HWA wires. Another popular technique widely used to assess free-stream disturbances is the pitot probe.[25, 49–53] Although the technique is easy to realize, it suffers from a number of drawbacks. For instance, to avoid protective cavities, which lead to frequency-dependent damping effects and resonances, the transducers need to be flush-mounted facing the stagnation conditions. In shock tunnels, this puts the transducers at risk of excessive thermal loading and particulate impact. Furthermore, Chaudhry et al. [54] studied the transfer function of various pitot probe geometries, considering fast acoustic, slow acoustic and entropy disturbances. The transfer functions were found to be a strong function of the shock stand-off distance and the probe geometry, which is not standardized, and thus makes the comparison of results obtained with different probes difficult.[55] A promising alternative to intrusive techniques is the non-intrusive focused laser differential interferometer technique applied by Parziale et al. [56] to conduct quantitative measures of density fluctuations in the reflected shock tunnel T5. The technique was first described by Smeets [57] and exhibits a very high frequency response (above $10\ \mathrm{MHz}$) and an adequate spatial resolution. The technique is limited to density fluctuations and unfortunately cannot easily be transferred between different facilities due to its elaborate setup.

Ali et al. [58] investigated the free-stream disturbance spectra in a Mach 6 wind tunnel by means of a cone probe in combination with HWA and a pitot probe. The experimental activities were complemented by a numerical study conducted by Schilden et al. [59]. The combined study also aimed for decomposing the measured free-stream disturbances into the three disturbance modes as introduced by Kovasznay [60]. For the investigated test cases the acoustic mode was found to be about one order of magnitude higher compared to the entropy mode whereas the vorticity mode was found to be negligible, which is in line with Pate's observation [61].

For tests in HEG a wedge shaped probe was designed with the purpose of providing an easy-to-implement technique, to assess free-stream disturbances, also suitable for harsh test environments. The probe was designed to measure pressure, temperature and heat flux fluctuations at the surface of a slender body behind an oblique shock. The above requirements further imply that protective cavities around the transducers need to be minimized to ensure an undisturbed frequency response of the transducers. Regarding the probe dimensions a compromise was found, providing enough internal volume to integrate various types of transducers as close as possible to the leading edge while reducing the probe size to allow the integration into test sections in addition to a standard wind tunnel model. The basic dimensions of the probe head are $80\text{x}116\ \mathrm{mm}$ in downstream and spanwise direction with an opening angle of $40°$. The probe is equipped with an exchangeable plane insert allowing the aerodynamically smooth integration of a wide range of transducers, while allowing the instrumentation to be adopted to different test conditions by changing the instrumented insert. Furthermore, the insert includes the leading edge of the probe which helps to avoid steps or gaps on the probe surface. The leading edge radius was chosen to be $0.1\ \mathrm{mm}$, allowing repeatable manufacturing. The probe can be used at different angles of attack to increase the signal-to-noise ratio in low pressure or low temperature environments. Since the probe extension is limited in the spanwise direction, side effects, dependent on the angle of attack and the Mach number, need to be considered. To assess the effect of the limited probe extension 3D RANS computations at Mach 3, 6 and 7.4 were conducted using the DLR TAU code [62, 63]. The computations reveal that, although side effects are present at the probe limits, an undisturbed region of constant surface pressure exists in which the instrumentation is placed.

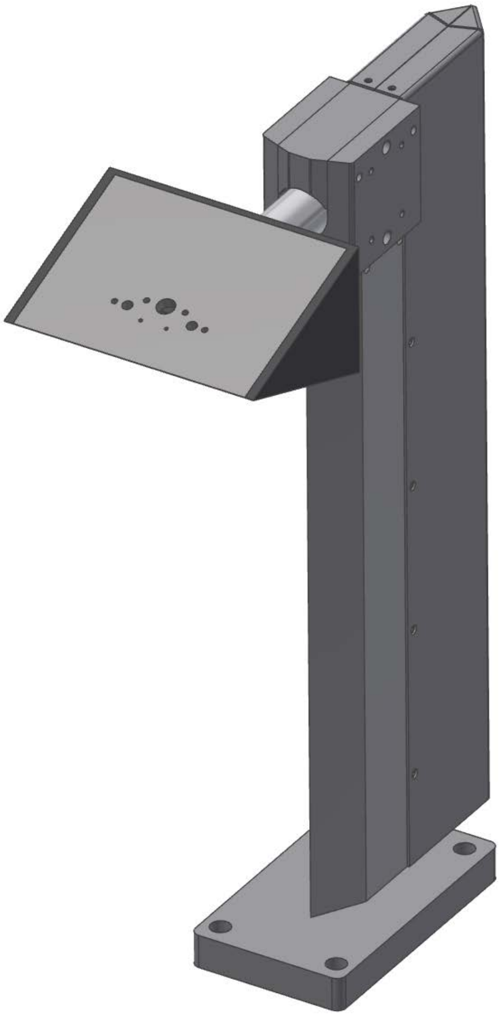

Figure 3: The HEG wedge probe to assess free-stream disturbances in harsh test environments.

Figure 4 shows the amplitude spectra (AS) obtained using the wedge probe in HEG at Mach 7.4. The AS in the figure corresponds to the signal rms in a 1 kHz frequency window. Piezoelectric transducers were used to cover the depicted frequency range. Figure 6 depicts the normalized surface pressure rms evaluated in a frequency range spanning from $1\ \mathrm{kHz}$ to $50\ \mathrm{kHz}$. Results obtained in two additional hypersonic wind tunnels, both Ludwieg tubes, using the wedge probe are included in the figure and show that the probe can be applied in a wide range of test conditions in different wind tunnels. Detailed information on free-stream disturbance measurements using the wedge probe are available in Wagner et al. [9].

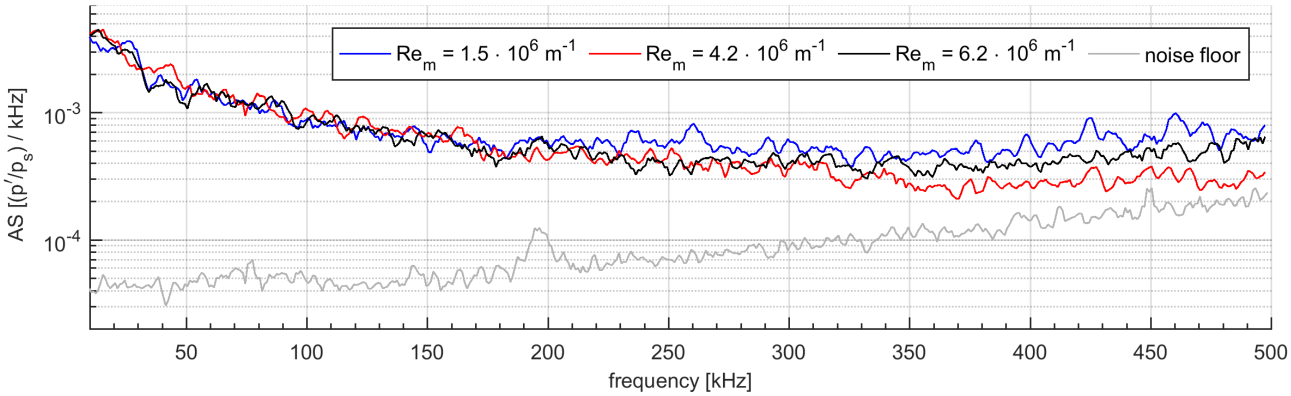

Figure 4: Amplitude spectra (signal rms in a 1 kHz frequency window) measured using piezoelectric transducers on the wedge probe in HEG at Mach 7.4. [9]

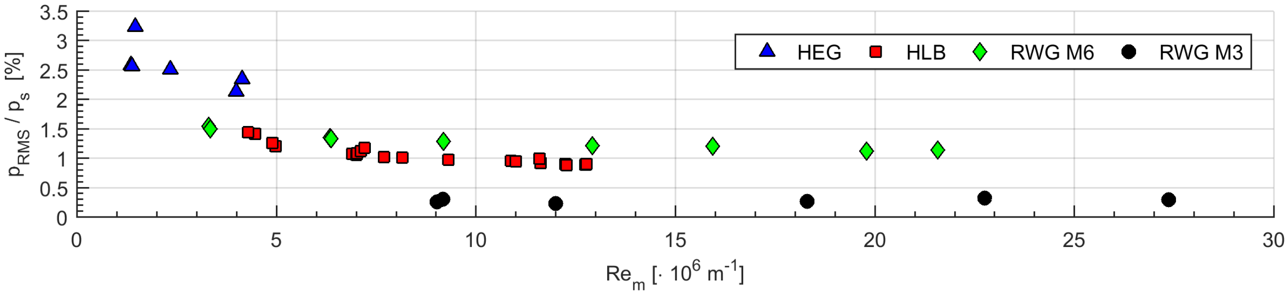

Figure 5: Surface pressure rms normalized by mean surface pressure evaluated between 1 kHz and 50 kHz. [9]

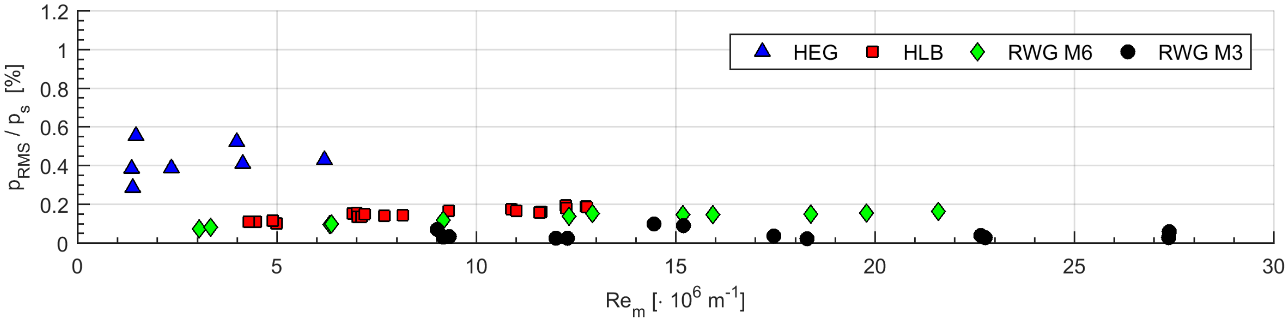

Figure 6: Surface pressure rms normalized by mean surface pressure evaluated between 200 kHz and 300 kHz. [9]

4.0 HYPERSONIC BOUNDARY LAYER TRANSITION

Numerous studies on hypersonic boundary layer transition were conducted in hypersonic shock tunnels and are available in the open literature. The scope of the present manuscript is not a review of all studies. Instead, a comparative study between two shock tunnels using the identical wind tunnel model will be introduced in section 4.1. The study is of particular interest since it revealed significant differences of the transition locations in both tunnels at comparable test conditions. It is an excellent example how unknowns in e.g. the free-stream disturbance environment can affect the transition process and why these unknowns need to be explored as described in section 3.0. Furthermore, various transition control strategies are briefly introduced while more detailed informations are provided for ultrasonically absorptive surfaces.

4.1 Comparative Transition Studies in HEG and HIEST

Comparative hypersonic boundary layer transition studies were conducted in the JAXA HIEST shock tunnel (Japan) and HEG. A blunted 7° half-angle cone with an overall length of 1100 mm and an exchangeable nose tip was used in HEG and the HIEST shock tunnel. The model was designed and manufactured by JAXA. Its overall layout is related to the forebody of the HIFiRE I flight experiment. Comparable test conditions were chosen in both facilities and the same instrumentation was used to assess the transition process on the model.

The study revealed a strong unit Reynolds number effect in both facilities. Furthermore, the transition process from laminar to turbulent differs between the facilities which is accompanied by a significantly larger transition length and a later transition location (based on heat flux increase) in HIEST compared to HEG, figure 7. Transition Reynolds numbers and N-factors tend to be higher in HIEST as well. Surface pressure measurements using fast response piezoelectric pressure transducers in combination with boundary layer stability analysis using the DLR NOLOT code proved the presence of second mode instabilities in both facilities. A detailed description of the study is provided in Wagner et al. [64]. Second mode instabilities were also found in high speed Schlieren images taken in HEG, figure 8. The wavelet analysis of the schlieren image shows the instability wave packet in the boundary layer above the model wall. The wavelet analysis further allows to filter the image information in different frequency ranges which allows to isolate the fundamental wave and the first harmonic of the

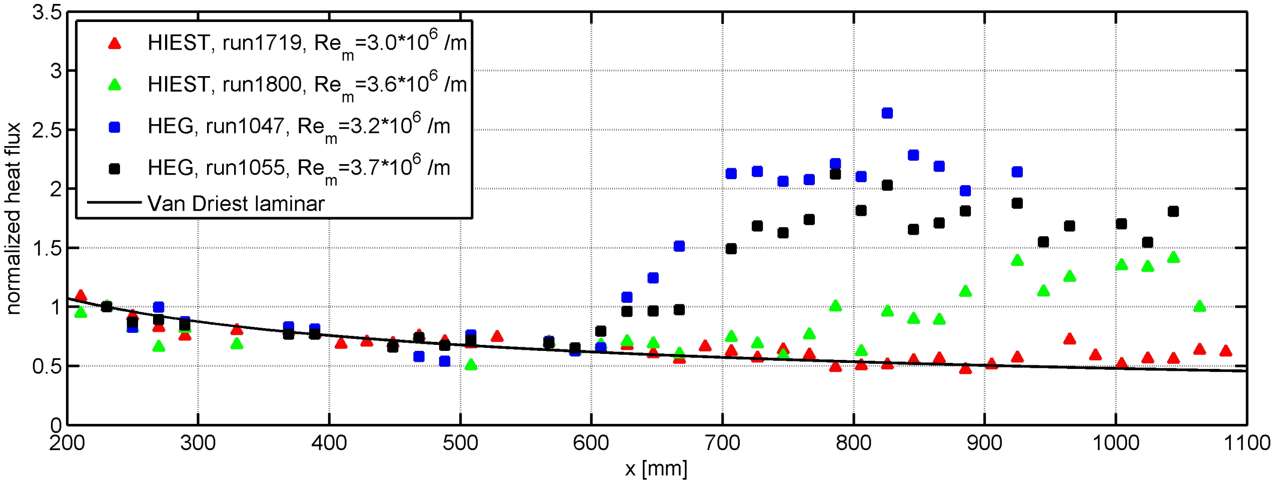

Figure 7: Normalized heat flux distribution on a 7 ° cone with 2.5 mm nose radius in HEG and HIEST. [64]

second mode instability from the image noise. A detailed study of the second mode wave packets by means of wavelet analysis is provided in Benjamin [65]. The proof of the existence of the second mode instability and its dominance in the transition process allows to develop possible control strategies as will be discussed in the following section.

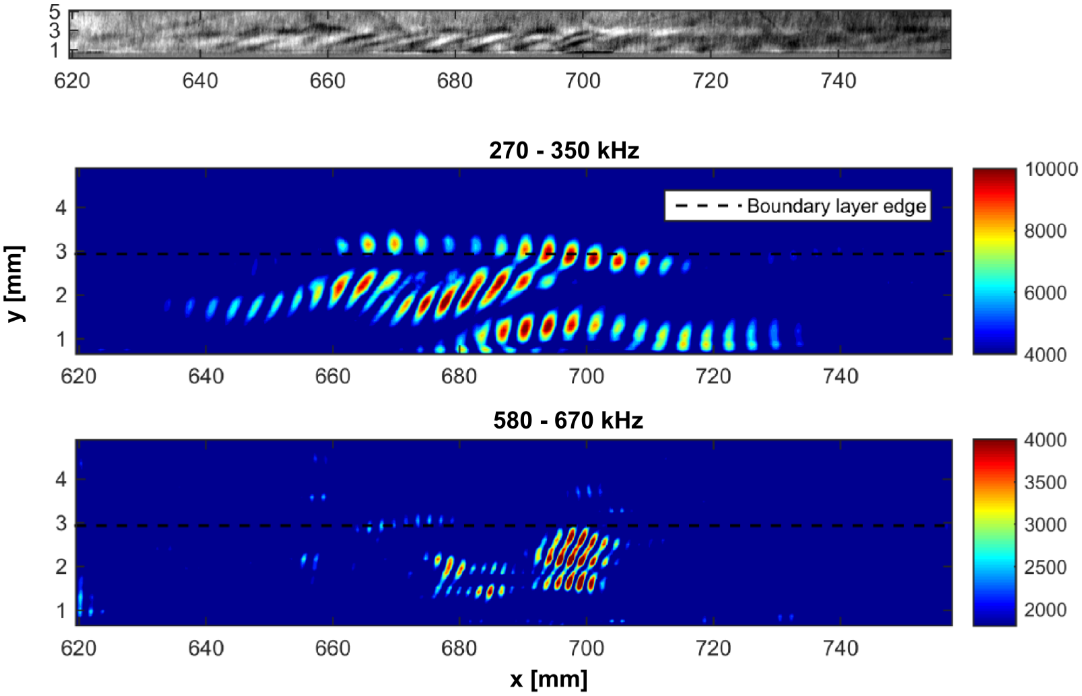

Figure 8: Wavelet analysis applied to a schlieren image (top) to capture the fundamental wave of the second mode instability (middle) and the first harmonic (bottom).[65]

4.2 Transition Control Strategies

Vehicles that would benefit most from transition control, resulting in a delay of transition, are those travelling over a long period of time at hypersonic speeds such as airbreathers or gliders. In contrast, reentry vehicles and missiles are due to their short peak-heating times less sensitive to transition. In general, transition control strategies can be active or passive. They can be used to trip the boundary layer or to postpone the transition process. For the latter, active strategies modulate the boundary layer at frequencies comparable to the frequency of the travelling instability wave. The topic is subject to present research typically using electrical discharge devices which can generate high frequency disturbances up to 1 MHz and above [66–69] or plasma generators [70–74].

Passive control strategies are more robust and thus more likely to be realised first on hypersonic systems. To successfully control transition the dominant instability mechanism leading to transition needs to be identified. A detailed description of hypersonic transition mechanisms is provided by Saric et al. [75]. Based on the identified dominant instability the following strategies can be followed to control transition (in any sense):

- body shaping (e.g. nose bluntness, surface curvature, cross flow avoidance) [76–78]

- roughness / surface waviness [79–81]
- blowing/suction [82–85]
- local surface heating/cooling [86–90]
- 2nd mode damping by relaxation processes in high enthalpy flows [91, 92]
- acoustically absorptive surfaces. [4, 5, 28, 93]

The latter strategy will be further discussed in the following section.

Passive Control by Acoustically Absorptive Surfaces

4.2.0.1 Absorption Characteristics of Surfaces with Random Micro-Porosity

To determine the ultrasonic absorption characteristics of porous materials a test rig was designed to transmit ultrasonic wave packets of discrete frequencies at an angle of incidence towards porous samples and a solid reference sample. The transmitted waves are reflected at the surface and subsequently recorded for evaluation. The comparison of the amplitudes of the reflected wave packages allows to assess the reflection coefficient of the material, $R = A_{porous}/A_{solid}$, and thus the absorption properties in the ultrasonic frequency range. A schematic of the experimental setup and an investigated porous CC-SiC sample is shown in figure 9. The procedure follows an approach used by Fedorov et al. [94]. It is described in detail in Wagner et al. [95]. Applying this test procedure the reflection coefficient depicted in figure 10 are obtained. It can be seen that the investigated material significantly damps acoustic waves which interact with the surface. Furthermore, a clear frequency dependence of the absorption process can be observed.

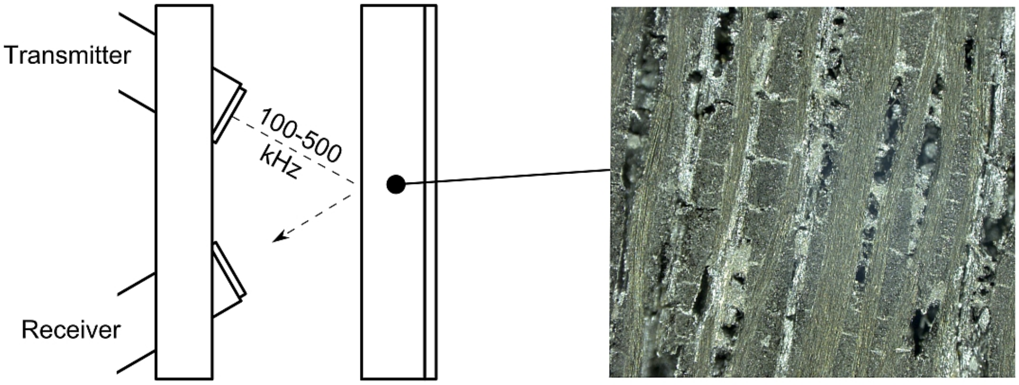

Figure 9: Schematic of the experimental setup to assess the ultrasonic absorption properties of porous ceramics.

The obtained results provide a first estimation of the material performance with respect to instability damping. Therewith, an inexpensive method is established to evaluate porous materials before wind tunnel tests are carried out. By determining additional material properties such as for instance porosity, flow through resistance and pore size acoustic absorber theory can be used to predict the material performance for application ranges of interest, Wagner [95].

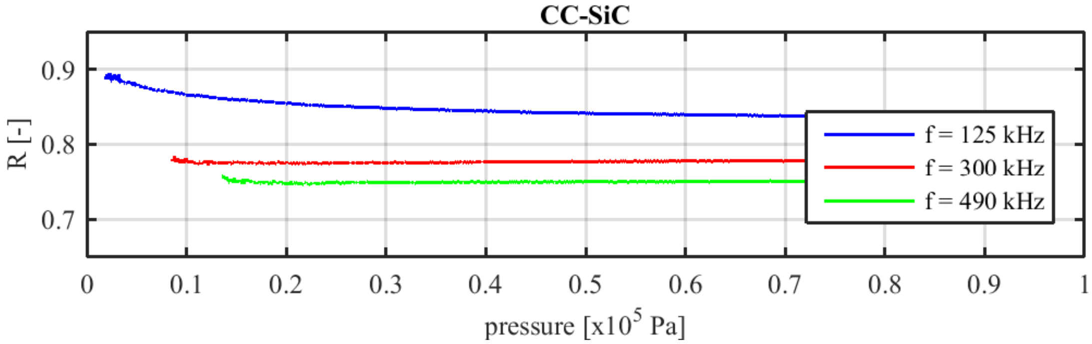

Figure 10: Measured reflection coefficient of a CC-SiC. [6]

4.2.0.2 HEG Wind Tunnel Model

A 7° half-angle blunted cone with an overall length of $1100\,\mathrm{mm}$ and an exchangeable nose tip was used to study passive hypersonic boundary layer transition control by porous coatings in HEG. For the experiments nose radii of $2.5\,\mathrm{mm}$ and $5\,\mathrm{mm}$ were used. The model was equipped with a $835\,\mathrm{mm}$ long insert of ultrasonically absorptive carbon-carbon ceramic (C/C). The insert started at $182\,\mathrm{mm}$ measured from the $2.5\,\mathrm{mm}$ model tip and covers 122° of the model surface in circumferential direction, figure 11. To minimize potential discontinuities at junctions the model was machined with the C/C insert installed. The model was equipped with 49 flush mounted coaxial thermocouples to measure the transition location by means of surface heat flux evaluation. Furthermore, 12 piezoelectric fast response pressure transducers were flush mounted on the solid surface and the porous surface. The transducer positions on the model were chosen based on the experience gathered in previous studies, Wagner et al. [96].

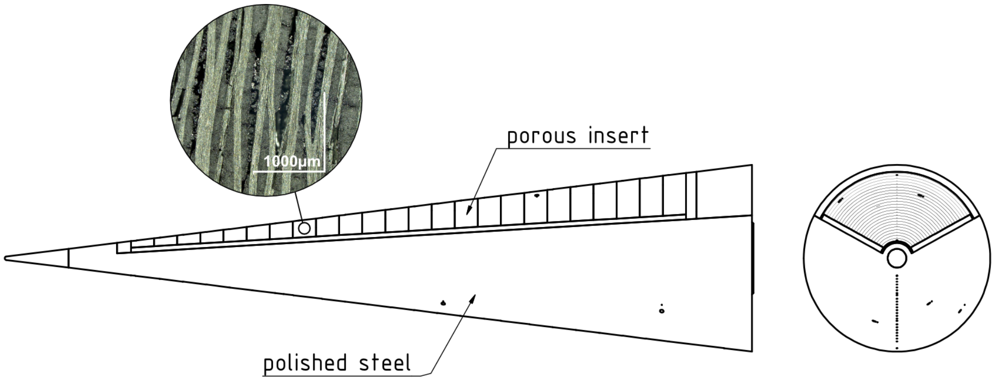

Figure 11: Technical drawing of a 7 ° half angle cone model with porous insert for passive transition delay. The total length of the model is $1100\,\mathrm{mm}$.

4.2.0.3 Transition Delay

According to section 4.2.0.1, porous ceramic materials should be able to damp the second mode instability. Consequently, a transition process dominated by the latter instability should be delayed.

To resolve the second mode wave packets in the surface pressure measurements a continuous wavelet transform using the Morlet wavelet was used. Figure 12b and 12c show the coefficients of the wavelet transforms for a frequency range between $100\ \mathrm{kHz}$ and $1\ \mathrm{MHz}$ on the smooth and the porous surface at $\mathrm{x} = 785\ \mathrm{mm}$ of the cone. A high coefficient represents the presence of a second mode instability. Figure 12a shows the smoothed surface pressure traces of the evaluated transducers in the time interval of $0\ \mathrm{ms}$ to $7\ \mathrm{ms}$ after shock reflection. The wavelet analysis reveals that the second mode instabilities on the reference surface appear about $1\ \mathrm{ms}$ after flow arrival. They remain present during the complete test time window which is defined between $3\ \mathrm{ms}$ and $6\ \mathrm{ms}$. Furthermore, the instabilities are not continuously present in the the boundary layer. Instead, they are grouped in wave packets. Finally, the comparison between the porous surface and the reference surface confirms that the applied porous ceramic (here CC) is effective in damping the second instability, figure 12b and 12c.

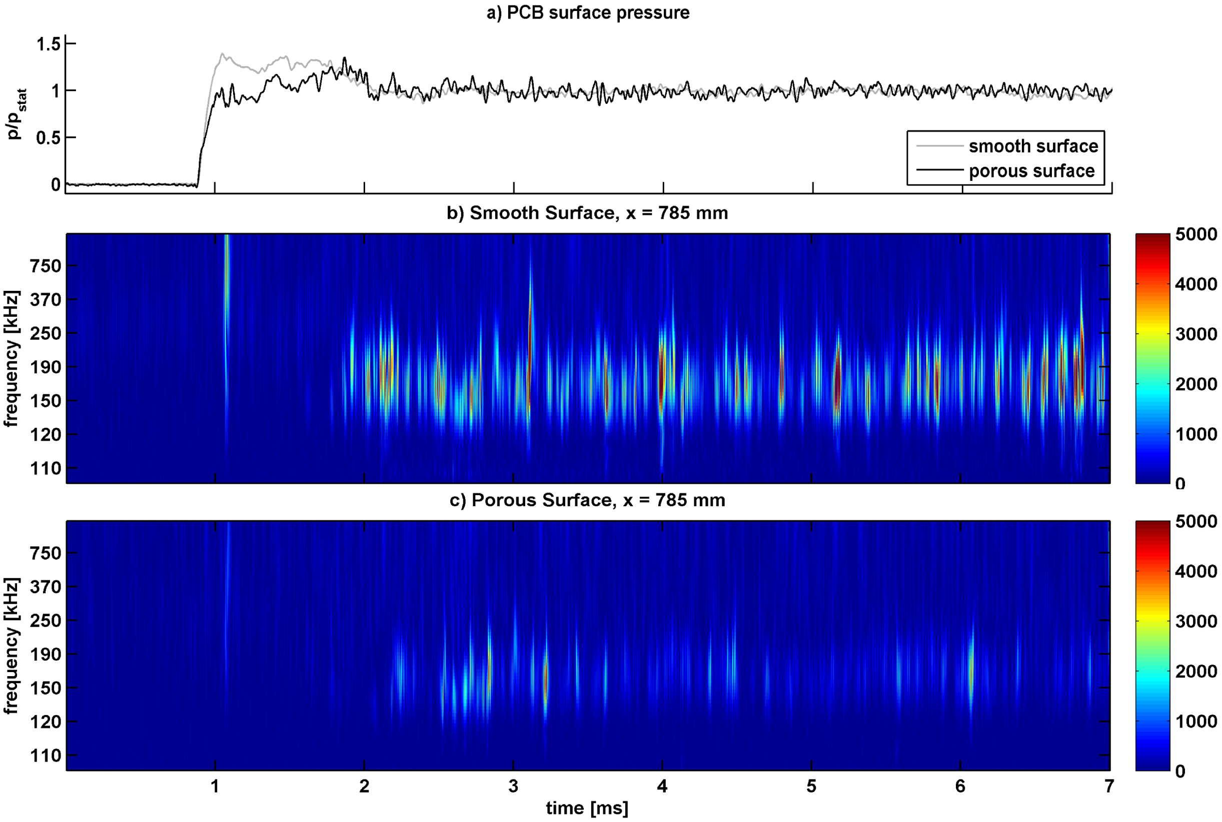

Figure 12: Wavelet analysis of the surface pressure on the cone showing a reduction of the second mode instability amplitude above the porous surface in HEG. [97]

Ultimately, figure 13 shows the expected transition delay by depicting the normalized surface heat flux on the cone at various unit Reynolds numbers on the smooth and the porous surface. It is clearly visible that the characteristic heat flux rise associated with the transition process occurs further downstream on the porous

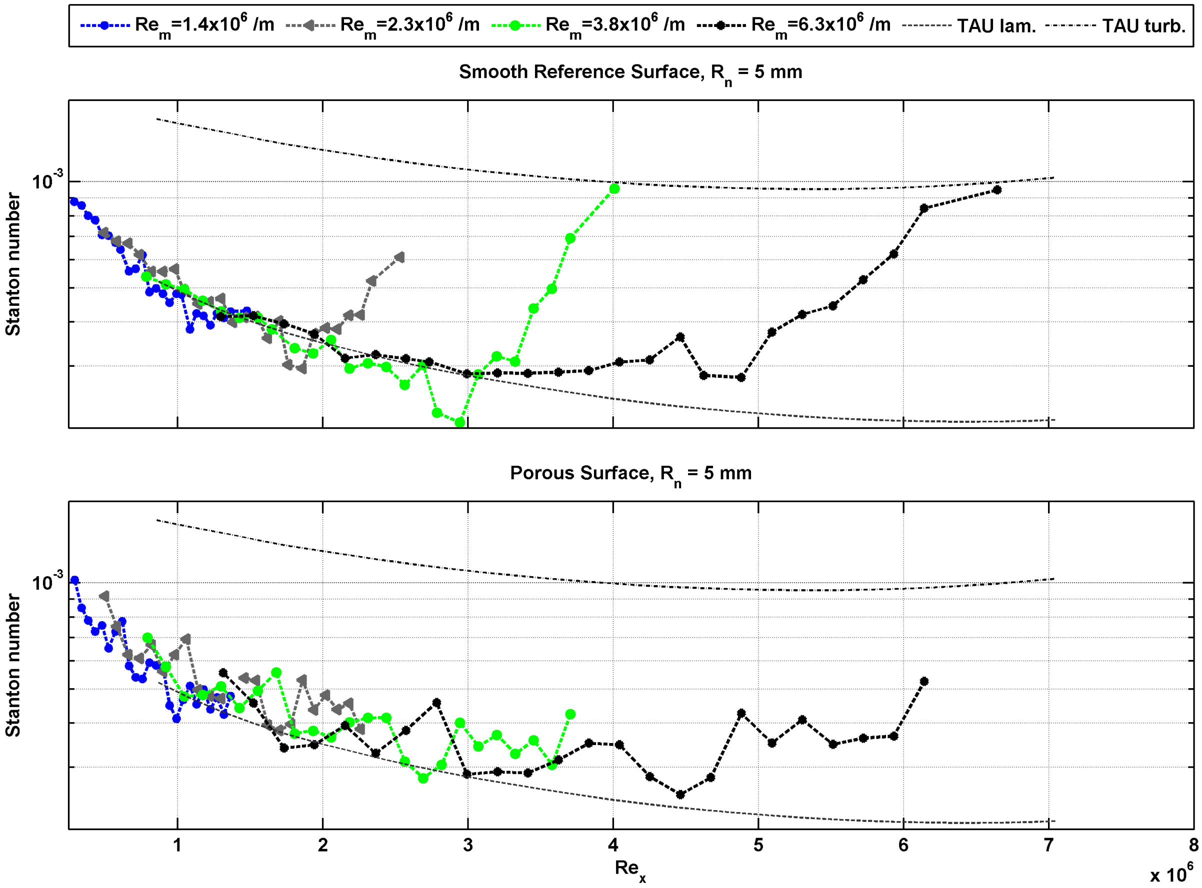

Figure 13: Normalized heat flux distribution on the cone above a smooth and a porous surface showing a significant delay of the transition process on the porous surface for different unit Reynolds numbers. [97]

surface compared to the smooth surface. After successfully proofing the concept a design approach was set up to allow a targeted material development, optimized for a predefined application range. The new materials will be CC-SiC ceramics and will not only have improved acoustic properties but will also be temperature stable to resist heat loads present in hypersonic sustained flight. To facilitate the optimization process between material development, manufacturing and testing a test bench to inexpensively access the reflection coefficient of new materials was setup. This allows to investigate a number of possible ceramics and to finally chose the most promising candidate for wind tunnel or flight tests.[6]

5.0 CONCLUSION

Hypersonic high enthalpy facilities play an important role in the field of boundary layer transition research. Although these facilities, in general shock tunnels, have a number of drawbacks such as short test times and harsh test environments, they provide access to typical flight conditions which cannot be covered by cold hypersonic facilities. Efforts are taken to determine the free-stream disturbance levels in shock tunnels. Although it is a challenging task, progress has been achieved by introducing a wedge shaped probe which was successfully used in HEG and two additional cold hypersonic facilities at Mach 3, Mach 6 and Mach 7.4. The test conditions found in HEG promote the second mode instability to be the dominant instability leading to transition on slender models with predominantly 2D flow fields. This allows to investigate passive transition control strategies targeting this instability. Ultrasonically absorptive carbon-carbon materials were shown to reduce the second mode amplitudes resulting in a significant delay of transition on a cone model in HEG. Present and future efforts aim to develop temperature stable ultrasonically absorptive materials tailored to predefined test conditions.

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