Physical aspects of highly-compressible boundary layers and their applications

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February 1, 2024

Flight systems operating at high-speeds can be quite different: aircrafts, rockets or reentry vehicles, but they are all enveloped by turbulent, hot, highly compressible flow with possible chemical non-equilibrium. These effects become dominant in a very thin region in the proximity of solid boundaries, called the boundary layer. Here are summarized some of the relevant aspects concerning this extremely important region and how each one can play a part in solving several technical challenges concerning the engineering design of high-speed vehicles.

1 Overview

The design of supersonic and hypersonic aircrafts and reentry vehicles has become a subject of major interest in the recent years for public and private institutions regarding several revolutionary applications like space exploration and commercial aviation. As the vehicle moves through the atmosphere at several times the speed of sound, aerodynamic drag and heat transfer become determining factors concerning the applied thermal and mechanical loads. This regime starts traditionally when the vehicle approaches five times the speed of the sound waves in the free stream (which gives a Mach number $M_\infty = 5$), and corresponds to applications of high-speeds atmospheric flights at low altitudes. Recently, Urzay (2018) made a comprehensive study on the technical challenges that have to be overcome to enable supersonic propulsion systems that can accelerate aircrafts to very high speeds, reviewing some of the state-of-the-art flight prototypes. If we consider the flow dynamics around the flight system as a whole, it's very difficult to discern all the different physical processes that are often coupled with each other. For this reason, engineers often try to simplify the problem, considering very simple configurations that can nevertheless give important hints on the flow physics. One of these configurations consist in a flow passing above a flat plate, in which the flow is brought to rest by the friction with the wall, generating strong velocity and temperature gradients. Figure 1 show an example of this flow, highlighting the strong density variations (and consequently related quantities) that are the reason why often high Mach regimes are referred to as *highly compressible*, as opposed to the nearly *incompressible* nature of low-speed flows. In the next sections are discussed some of the relevant features that are often investigated by scientists to grasp how the physics evolve, and how they relate to the effects we observe on more complex systems.

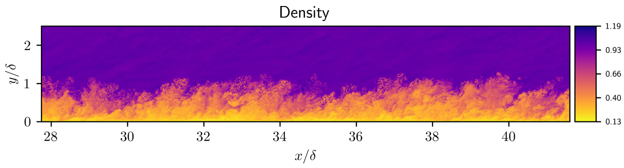

Figure 1: *Contours of density gradient in a turbulent boundary layer at Mach 6. Data taken from a current research project.*

2 Aerodynamic heating

One main aspect in which high-speed compressible boundary layers fundamentally differ from their incompressible counterparts is that the momentum and thermal fields are strongly coupled through the density.

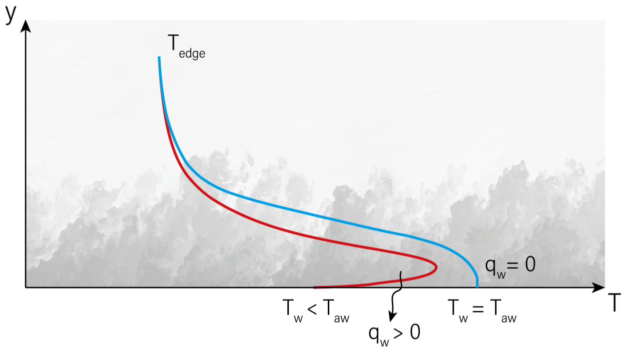

Figure 2: *Wall-normal temperature profile in the case of cooled wall (red line) and adiabatic wall (blue line). The local maxima of the left profile near the wall is associated with a strong aerodynamic heating in that region.*

The dependence on temperature of viscosity and thermal conductivity make the physics even more complex, promoting the energy transfer from kinetic to thermal. It can be shown that the square of the Mach number is proportional to the ratio between the kinetic energy and specific thermal enthalpy of the surrounding flow:

$$M_\infty^2 \propto E_{kinetic}/E_{thermal} \tag{1}$$

As the flow is brought to rest by the friction with the wall, the huge amount of kinetic energy carried by the flow is then converted into thermal energy, resulting in high temperatures and chemical dissociation. If the wall is assumed to be adiabatic, the wall-normal temperature profile will settle with a zero slope to a certain temperature T_{aw} (adiabatic wall temperature) that is always less than the stagnation temperature of the free stream, being the process non-isotropic. However, in most applications the wall is usually much cooler than the adiabatic wall temperature, resulting in large gradients in the temperature profile near the wall to respect the imposed isothermal boundary condition (Figure 2). This temperature gradient is due to viscous dissipation and is commonly referred to as *aerodynamic heating*. Here the description is limited to the conductive nature of heat transfer associated to thermal conductivity and wall temperature gradients:

$$q_w = -k_w \left(\frac{\partial T}{\partial y}\right)_w \tag{2}$$

It's important to note that another source of heat into the body (especially for reentry vehicles) is thermal radiation, which is due to the extreme temperature that are reached by the flow field (other details can be found looking at Anderson (2000)).

3 The heat barrier

The reader may be familiar with the famous *sound barrier*, which is associated with the peak of aerodynamic drag that an aircraft encounters when travelling at the speed of sound (Mach 1). Although initially this limit was thought to be impossible to overcome, technical solutions were found in the 1940s and 1950s to design supersonic aircraft for military and commercial purposes. Another similar challenge, the *heat barrier*, is found as the Mach number further increases, posing severe constraints in the airframe surface materials choice. As discussed in Section 2, fluid dynamics is essential to understand the amount of heat that is transferred to the solid wall as opposed to the part that is dissipated into the environment. Consequently, the choice of the surface material is a key factor, that is also a function of the specific flight envelope that a vehicle is designed for. This section aims to discuss some of the effects that become relevant in the boundary layer flow that are representative of a flight system approaching such extreme conditions. Three main aspects are highlighted:

1. Peak temperature rise in the boundary layer
2. Non-calorically-perfect gas effects
3. Chemical dissociation

The first aspect that plays an important role at high Mach numbers is that the peak temperature in the boundary layer (and therefore the exchanged heat with the wall) increases rapidly with M_∞. To give a sense of the rate in which this increase takes place, it can be shown that q_w is proportional to the free stream velocity elevated to the $cube$, as opposed to the quadratic dependence of the aerodynamic drag (Anderson, 2000). Another important point, that show clearly the complexity of this flow regime, is that the perfect gas assumption can not be considered valid anymore. The reason for this inadequacy is that in practice when the aerodynamic heat start to rise, the excess of thermal energy can activate chemical processes in reacting gases, which provide energy for the chemical conversion of the molecules. The perfect gas assumption can not represent this physical processes and instead overpredicts the gas temperature with large errors. This consideration directly leads to the third point: chemical dissociation. For example, at sea level, oxygen begins to dissociate at $T \approx 2000K$ while nitrogen at $T \approx 4000K$. Reaching higher temperatures, dissociation processes are enhanced and eventually lead to ionization ($T \approx 9000K$). These effects change profoundly the flow physics, especially in the prediction of post-shock quantities.

4 Turbulent fluctuations

The aerothermal field is not only characterized by strong gradients of averaged quantities but also by intense turbulent fluctuations. In compressible flows, the average process of a given quantity f is indicated as $\tilde{f}$, while its fluctuations over the mean value are indicated as f''. To estimate the mean intensity of a

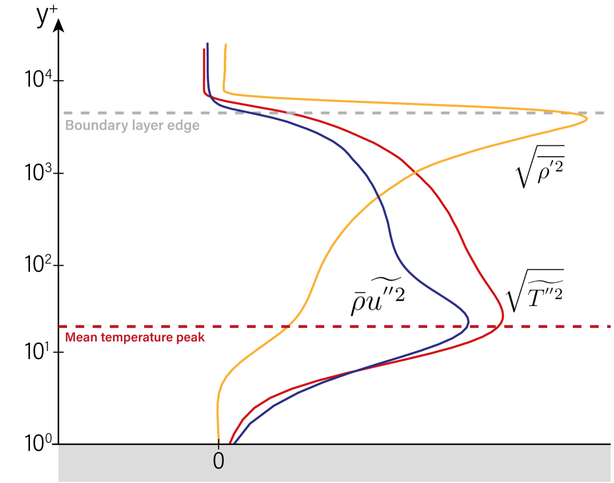

Figure 3: *Schematics of the turbulent fluctuations in the wall-normal direction of a turbulent compressible boundary layer at Mach 6. The mean temperature peak and boundary layer edge are indicated with dashed horizontal lines for reference.*

given quantity fluctuations, root-mean-square value (rms) if often computed as $(\widetilde{f''^2})^{1/2}$. Here are reported the rms profiles of streamwise velocity, static temperature and density fluctuations to address their behaviour along the boundary layer length. The distance from the wall is indicated by the adimensional wall-normal coordinate $y^+ = y/l_\nu$, which is obtained using the characteristic length l_ν that highlights the contribution of viscous and turbulent stresses (see Pope and Pope (2000) for more details). Interestingly, the peaks of velocity and temperature fluctuations occurs around $y^+ \simeq 10$, where the mean temperature peak occurs. The peak of the rms of density fluctuations occurs at the edge of the boundary layer, indicating that compressibility effects are most intense in the fluctuating field when the flow transit from the free-stream region to the hot, turbulent boundary layer. More results that includes the rms of molar fractions are summarized in Urzay and Di Renzo (2021).

5 Boundary layer transition

Until now, the boundary layer has been treated as turbulent, meaning that the flow near the wall is chaotic and irregular, generating high turbulent fluctuations and energetic vortices. However, when a flight system reenters the atmosphere the flow is initially well-ordered and non-chaotic, which is called the laminar state. The transition from these two states can occur for different and complex reason (mainly associated with the amplification of air's local velocity and pressure instabilities), but when it happens, the aerodynamic drag and heat are deeply aggravated. Since this process is not avoidable, engineers must predict and control the transition to optimize in the best possible way the vehicle's thermal and mechanical responses. What we know about the boundary layer transition at this regime is by no means satisfactory, in fact very recent studies are tackling this problem to uncover some of the physical processes that have been ignored until now. One example is the work of Di Renzo and Urzay (2021), in which a Mach 10 transitional hypersonic boundary layer at suborbital enthalpies is analyzed using direct numerical simulations. Their simulations accounted for thermochemical effects and their interaction with turbulence, which is a crucial aspect of study for high-speed flight on the upper part of the atmosphere, where large values of Mach and Reynolds number are attained combined with high stagnation enthalpies.

6 High-speed transportation

As the world becomes more and more connected, there are still huge distances separating us that can only be covered in several hours by commercial airplanes. Two decades have almost passed since the famous supersonic commercial aircraft *Concorde* retired, but a great interest is picking up in the return of high-speed commercial travel for different purposes, such as transportation of passenger and goods or access to space. What is different now is that the research is focusing on planes that can fly on sub-orbital trajectories, thus avoiding the lower parts of the atmosphere except for take-off and reentry. This is less problematic from a national regulations point of view because at that altitudes the sound is dissipated before arriving to cities and residential areas. However, this kind of flight requires a new class of hyperplanes that can resist the huge mechanical and thermal loads that were discussed before in this study, but promise to revolutionize the way we travel and open new types of possible services like the fast transportation of critical medical supplies. To give a sense of the speeds that these vehicles can endure, many concepts proposed by private and public agencies promise that they can connect New York and London within one hour, with the possibility to provide almost zero emission from the propulsion systems. Looking at the aerodynamic efficiency of high-speed vehicles, which is measured by the ratio between the aerodynamic lift and drag L/D, it can be discouraging to learn that it is relatively low at high Mach numbers (Anderson, 2000). This is due to the rapidly increasing shock-wave strength that greatly affects the wave drag (aerodynamic drag due to the presence of shock waves). However, there is a class of cleverly design vehicles, called *waveriders*, that can generate higher values of L/D than other shapes (Figure 4). Since a major increase in drag is due to the fact that the high pressure behind the shock wave under the vehicle *leak* around the leading edge to the top surface, their design is optimized to have an attached shock wave all along their leading edge to generate more lift than other vehicles at the same angles of attack. Despite

Figure 4: *Artist's concept of X-43A waverider. Image adapted from the NASA website.*

the design being firstly driven by considerations on the wave drag, which can by estimated with the inviscid shock-expansion theory, the optimization process involve the control of viscous processes, trying to reduce the related skin-friction drag. In this context, predicting the transition to turbulence of the boundary layer and the amount of aerodynamic heat that is generated is essential to compute the thermal and mechanical loads on the vehicle. For example, surface roughness can be used to anticipate the transition to turbulence, which that can deeply change the overall flow dynamics on the vehicle. In conclusion, although the hypersonic waverider is still a technology of the future, the study of the associated flow physics especially for boundary layer flows can lead to major breakthrough in this field. The desire to overcome technical challenges in aeronautics and astronautics has led in the past to ingenious solutions that brought unthinkable milestones. A similar attitude is crucial to the development of hypersonic vehicles, which can revolutionize the way we travel here on Earth and access to space.

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