1 Introduction

If you can walk away from a landing, it's a good landing. If you use the airplane the next day, it's an outstanding landing.

General Charles "Chuck" Yeager (1923–)
First pilot to exceed Mach 1 in level flight
on October 14, 1947 in Bell X-1 aircraft

1.1 Background

The flow past an aerodynamic vehicle at high speed is characterized by complex phenomena. The vehicle shape produces multiple shock waves, as shown in Fig. 1.1 for a supersonic aircraft. The boundary layer formed at the solid surface can transition from laminar to turbulent, as seen in Fig. 1.2 from Schneider (2004). Intersections of shock waves with boundary layers form adverse pressure gradients and can cause boundary layer separation, as shown in Fig. 1.3. The nature and details of these flow phenomena depend on a variety of factors including the vehicle shape, Mach number, orientation (e.g., angle of attack), and altitude.

Control of the mean and fluctuating aerothermodynamic loading (i.e., surface heat transfer and pressure) may be important to avoid material failure. An example is Flight 2-53-97 of the X-15 hypersonic research aircraft on October 3, 1967 piloted by William J. ("Pete") Knight (Thompson 1992). A dummy ramjet engine was attached to a pylon beneath the aircraft fuselage (Fig. 1.4). During the flight at Mach 6.7 the shock waves generated by the dummy ramjet model and main wing leading edge intersected to form a shock–shock interaction resulting in the formation of a high-speed jet impinging on the dummy ramjet engine pylon and a significant increase in surface heating. Within less than three minutes the high heat transfer caused complete disintegration of a portion of the pylon structure (Fig. 1.5) composed of Inconel, whose melting temperature is approximately 1800 K. The flowfield structure generated by shock–shock interactions was subsequently investigated by Edney (1968*a*) and Edney (1968*b*) and

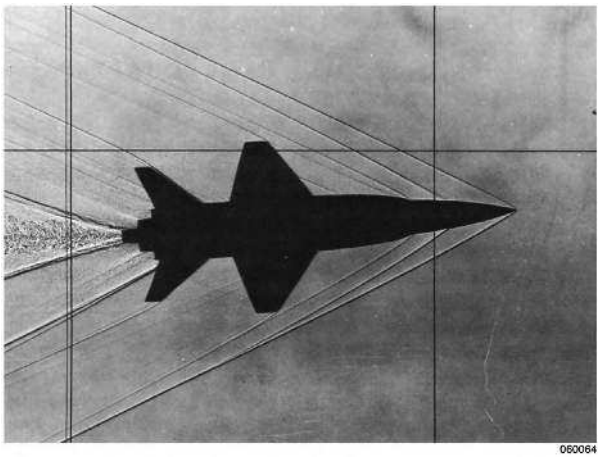


Figure 1.1 Multiple shocks generated by aircraft at supersonic speed. The variations in surface shape generate a sequence of shock waves and expansions (courtesy NASA).

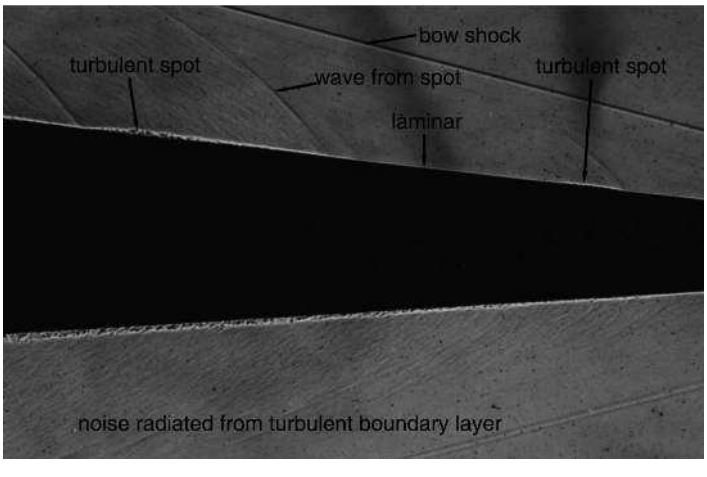
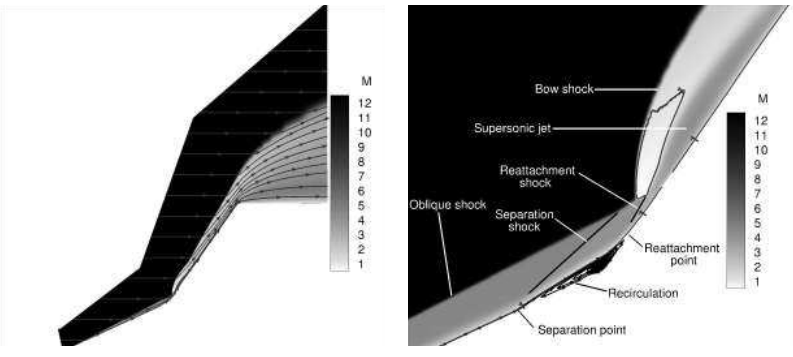


Figure 1.2 Boundary layer transition. A laminar boundary layer on a sharp cone at Mach 4.31 transitions to turbulent. (Schneider 2004, original figure from Dr. Daniel Reda).

a family of shock–shock interactions resulting in high surface heat transfer bear his name. The Edney IV interaction (Fig. 1.6) which caused the disintegration of a portion of the pylon produces peak heating up to an order of magnitude or more above stagnation point heating at the same freestream conditions.

Control of the flight of a high-speed vehicle is also important. Fig. 1.7 shows an artist's rendering of the Hypersonic Technology Vehicle 2 (HTV-2) developed by the US Defense Advanced Research Projects Agency (DARPA) as an unmanned experimental hypersonic rocket-powered glide vehicle. The plan for the first flight



(a) Double cone (b) Enlargement of corner region

Figure 1.3 Shock wave laminar boundary layer interaction on a double cone at Mach 12.82. The aft cone generates a shock wave that causes an adverse pressure gradient on the surface and separation of the boundary layer. The flow reattaches on the aft cone. The flow is from left to right (Kianvashrad and Knight 2018).

Figure 1.4 X-15 pylon (courtesy NASA).

Figure 1.5 Damage to pylon (courtesy NASA).

of the HTV-2 (Fig. 1.8) called for the vehicle to be launched from Vandenburg Air Force Base, California, on a Minotaur IV rocket, then separate from the launcher, achieve level flight, and glide above the Pacific Ocean at Mach 20 before purposely crashing into the ocean after 30 minutes of flight. Telecommunications contact with the vehicle ceased after nine minutes of the flight. The vehicle autopilot "commanded flight termination" after the vehicle began to roll violently due to loss of flight control. According to ABC News, US Air Force Major Chris Schulz, HTV-2 Program Manager for DARPA, stated "Here's what we know. We know how to boost the aircraft to near space. We know how to insert the aircraft into atmospheric hypersonic flight. We do not yet know how to achieve the desired control during the aerodynamic phase of flight. It's vexing; I'm confident there is a solution. We have to find it."

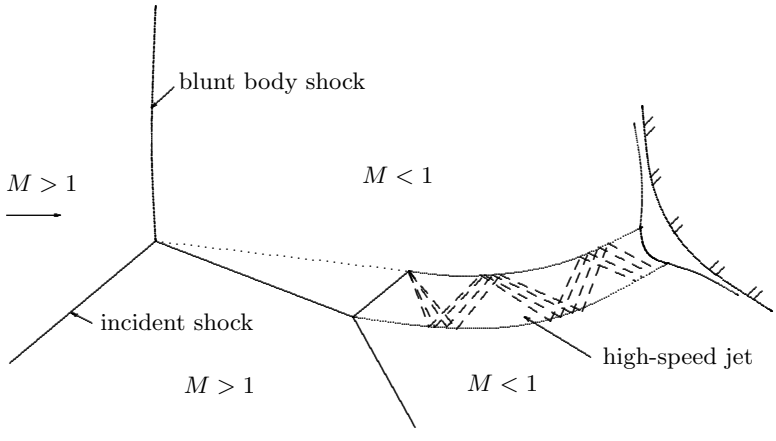


Figure 1.6 Edney IV interaction. The intersection of the external shock and blunt body shock creates a supersonic jet which impinges the body surface and causes high heating rates.

Figure 1.7 HTV-2 Hypersonic Technology Vehicle (courtesy of DARPA).

These two examples indicate the importance of *flow control* of high-speed vehicles. Recent reviews of flow control methods are presented, for example, by Gad-El-Hak (2007) and Cattafesta and Sheplak (2011).

1.2 Overview of the Book

The purpose of this book is to describe in detail a relatively new methodology for flow control – energy deposition by DC, laser, and microwave discharge. In

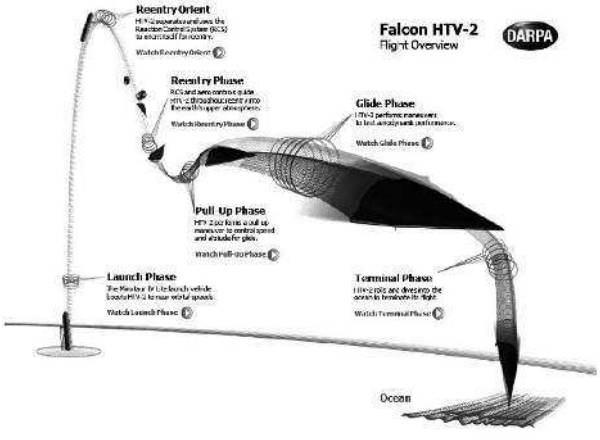


Figure 1.8 HTV-2 flight profile (courtesy of DARPA).

this context, *flow control* indicates modification of the flowfield in the vicinity of an aerospace vehicle by energy deposition. The book is organized as follows. Chapter 2 presents the fundamental equations governing energy deposition in a gas. Chapter 3 provides a background in statistical mechanics, and the development of the equations of continuum gas dynamics therefrom. Chapter 4 describes the dynamics and kinetics of charged particles. Chapters 5 through 7 provide a background for DC, microwave, and laser discharge. Chapter 8 presents models of energy deposition in an ideal gas. Chapter 9 describes applications of energy deposition for flow control.