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Aerodynamic heating in hypersonic flows

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A newly discovered mechanism can help keep the world's fastest jets from overheating.

For the last quarter of the 20th century, Concorde airliners and other supersonic aircraft shuttled wealthy passengers between North America and Europe at speeds of up to 600 m/s (about 1350 mph). The planes were retired in 2003. They had grown prohibitively expensive and worried passengers, who couldn't help but notice that the planes' windows were too hot to touch.

Today, however, several airlines have plans to reinstate jets capable of supersonic (Mach 1) and hypersonic (Mach 5) speeds—the Mach number is the ratio of a plane's speed to the local speed of sound. Mach 5 jets routinely exceed 1500–2000 m/s, depending on their altitude. A jet that fast could fly from New York to Paris in just 90 minutes.

Technical challenges have forestalled their development. The temperature of air passing over a jet increases with Mach number and has been measured at 2200 K on the surface of a plane flying at Mach 5 at an altitude of 20 km. Understanding where and when those high temperatures occur on an aircraft is critical to its performance and safety. This Quick Study explores a newly discovered mechanism that can reduce the heating of a jet's surface.

From laminar to turbulent

According to conventional wisdom, aerodynamic heating of a surface peaks with the onset of turbulence. Its emergence substantially increases the shear stresses in air adjacent to the surface, a process that converts kinetic energy to heat. Figure 1 visualizes a jet's hypersonic boundary layer—the thin layer of air whose flow speed decelerates to zero at the aircraft's bounding surface. The transition from laminar flow to turbulence, which is due to the amplification of air's local velocity and pressure instabilities, is unavoidable as air speed rises.

The image, obtained in a low-temperature hypersonic wind tunnel, is produced by laser scattering from carbon dioxide gas mixed with upstream air. In the cold air above the boundary layer, the gas solidifies into fine particles. But inside the boundary layer, where temperatures are much higher because of energy dissipation, the CO_2 remains gaseous. Light scattering from the cold particles appears white, whereas the gaseous flow appears black. The airflow, initially well ordered and laminar from left to right, is thus seen to become turbulent as air compression and expansion produce an amplifying acoustic wave.

The air is hottest when the flow is turbulent. Surprisingly, though, recent studies have shown that a comparable hot peak can also develop in the laminar region prior to the transition. The IR image, shown in figure 2a, of a flared cone in wind-tunnel experiments run at Mach 6 bears that out. A pre-turbulent heating peak, labeled "SH" for secondary heating, develops in an otherwise lower-temperature region prior to the emergence of the turbulent heating peak (TH).

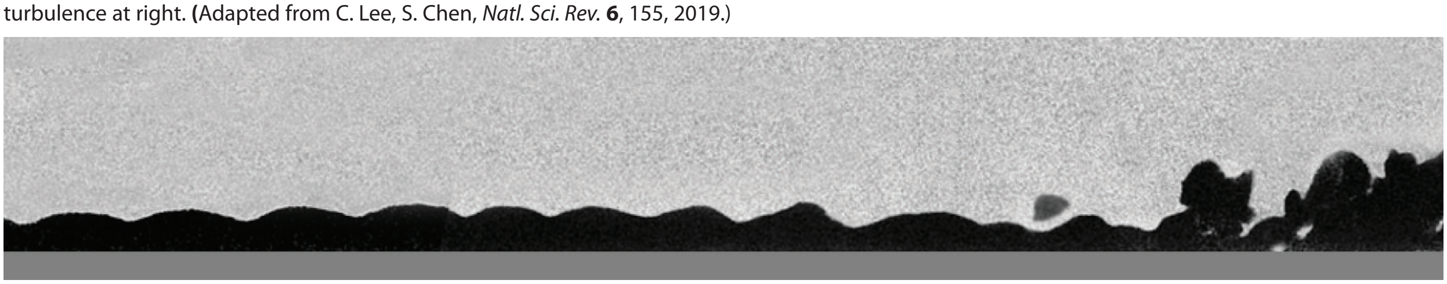
That pre-turbulent peak was first identified three years ago by Cunbiao Lee and his colleagues at China's Peking University. Their research revealed that the SH peak arises from a previously unidentified alternative aerodynamic interaction—one that can either increase or reduce surface heating, depending on circumstances.

Hypersonic heating

What accounts for two separate heating peaks? Three mechanisms convert mechanical energy to thermal energy in a hypersonic flow. The first is the viscous dissipation of kinetic energy by shear stresses adjacent to a surface. The second is also viscous dissipation but the result of normal stresses acting on the compressed air. And the third is the work done by pressure changes acting on the compressed air.

The two viscous energy conversion mechanisms are

FIGURE 1. RAYLEIGH SCATTERING reveals the transition from a laminar to a hypersonic boundary layer. Airflow is left to right in a Mach 6 air tunnel. The amplification of a high-frequency wave in the laminar region at left eventually results in the transition to surface turbulence at right. (Adapted from C. Lee, S. Chen, *Natl. Sci. Rev.* **6**, 155, 2019.)



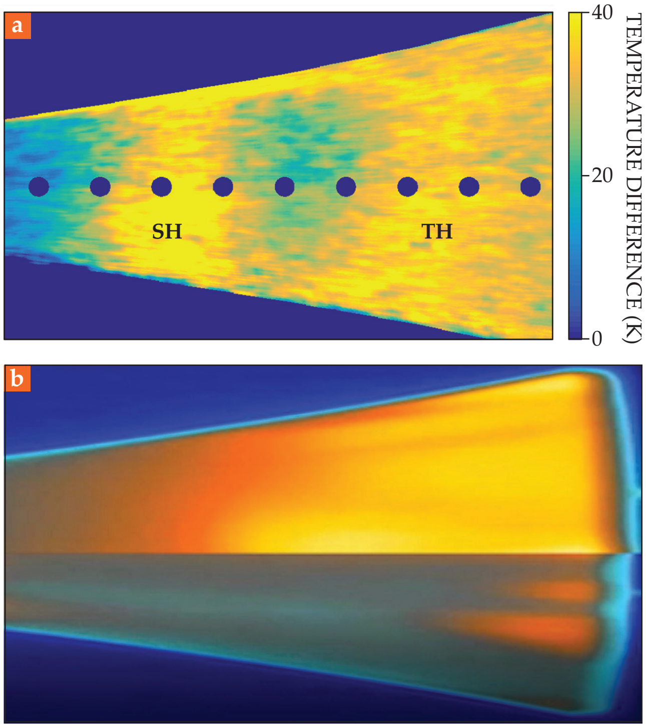


FIGURE 2. THE SURFACE TEMPERATURE of a flared cone rises in a hypersonic wind tunnel whose air is flowing at Mach 6. **(a)** An IR camera captures two (yellow) hot spots: one (SH) that arises from air-compression effects, followed by a second (TH) that arises from turbulent shearing stresses, or turbulence-induced friction. The blue region between SH and TH is the result of cooling by air expansion. Blue dots on the cone signify flush-mounted pressure sensors. (Adapted from Y. Zhu et al., *Phys. Fluids* **30**, 011701, 2018.) **(b)** Surface temperature within the SH region is imaged without (top) and with (bottom) acoustic-wave control introduced at the leading edge of the cone. (Courtesy of Cunbiao Lee.) For a video of the effect, see the online version of this article.

unidirectional—from mechanical to thermal energy—so they always dissipate kinetic energy into heat. Thus, the high-shear stresses that accompany the onset of turbulence always heat a surface. The peak labeled TH in figure 2a is an example.

But the SH peak that occurs prior to the turbulent region is caused by pressure work. Numerical simulations have shown that the magnitude and direction of that work depends on the phase differences between the periodic pressure fluctuations at the surface and air-density fluctuations in the flow. The upshot is that aerodynamic heating by pressure work is bidirectional: It can either augment or diminish the surface heating depending on the sign of those phase differences.

Engineering the cool

Pressure fluctuations behave as acoustic waves, which in hypersonic phenomena are known as second-mode waves. Although fluctuating pressure waves and air-density waves are normally of the same frequency in a second-mode wave, their phase differences—that is, the differences in where the waves peak—can vary. So when the waves are in phase (their peaks coincident), the pressure work will be positive and increase heating. But when the waves are out of phase (their peaks in opposition), the pressure work will be negative and reduce heating. Lee's group first discovered that heating mechanism in 2018, and it was recognized the same year as a new aerodynamic thermal mechanism by Bohua Sun at Xi'an University of Architecture and Technology in China and Elaine Oran at the University of Maryland in College Park.

The fluctuating pressure in hypersonic flows behaves as an acoustic wave and is controllable using either a porous surface or a wavy surface. Sound absorption on a porous surface can modify the phase difference of the acoustic wave enough to eliminate the SH peak shown in figure 2a. Alternatively, the use of an appropriately wavy surface can generate an acoustic wave that also modifies the phase of the natural pressure wave enough to reduce how much it heats the surface.

Figure 2b shows two IR images of the region of a flared cone where the SH peak is typically observed. When no wave control is applied to the cone, the upper panel exhibits a large SH peak (yellow). In contrast, the SH peak essentially disappears in the lower panel because of the acoustic control wave introduced by a porous surface near the leading edge of the cone. In general, either a porous or a wavy surface can reduce the surface heating by roughly 25%.

Through a series of detailed studies, Lee's group demonstrated the fundamental behavior of hypersonic transitions between laminar and turbulent flows, discovered a new aerodynamic heating mechanism, and developed successful strategies for controlling it. Through an understanding of the phase relationship between different types of waves, a physical basis for controlling certain aspects of high-Mach-number aerodynamic heating has emerged. How that control is applied to aircraft of the future remains to be seen.

Additional resources

▶ C. Lee, S. Chen, "Recent progress in the study of transition in the hypersonic boundary layer," *Natl. Sci. Rev.* **6**, 155 (2019).
▶ Y. Zhu et al., "Newly identified principle for aerodynamic heating in hypersonic flows," *J. Fluid Mech.* **855**, 152 (2018).
▶ Y. Zhu et al., "Acoustic-wave-induced cooling in onset of hypersonic turbulence," *Phys. Fluids* **32**, 061702 (2020).
▶ B. Sun, E. S. Oran, "New principle for aerodynamic heating," *Natl. Sci. Rev.* **5**, 606 (2018).
▶ W. Zhu et al., "Experimental study of hypersonic boundary layer transition on a permeable wall of a flared cone," *Phys. Fluids* **32**, 011701 (2020). PT