

New principle for aerodynamic heating

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Fluid flows that we encounter in nature are mostly turbulent. To date, the physics of turbulence has not been clear and is still considered as ‘the last unsolved problem in classical physics’. Its complex dynamical process reflects the strong non-linearity of the Navier–Stokes equation, which is a millennium math problem. The modeling and control of developed turbulence and the onset of turbulence, i.e. transition, are still bottlenecks in engineering applications such as aeronautics, astronautics and navigation.

Recently, hypersonic boundary-layer transition has become a strategic focus because of its severe impact on the aerodynamic force and heating of a high-speed vehicle. Compared to incompressible flows, hypersonic transition and its effect on aerodynamic heating are less understood owing to additional complexities such as second- and higher-order instability modes and non-linear coupling of different processes. With the development of test techniques, experimental research of a hypersonic quiet wind tunnel has become essential. A recent experiment was conducted at the Mach 6 quiet wind tunnel at Peking University, investigating flow over an instability-enhanced flared cone model, using three different Reynolds numbers. A host of measurement tools, including pressure sensors, temperature-sensitive paint (TSP), and particle image velocimetry (PIV), provided data for the analysis, using parabolic stability equations (PSE) and direct numerical simulations (DNS) [1].

The research was conducted in the State Key Laboratory for Turbulence and Complex Systems (LTCS) at Peking University. For the first time, the LTCS

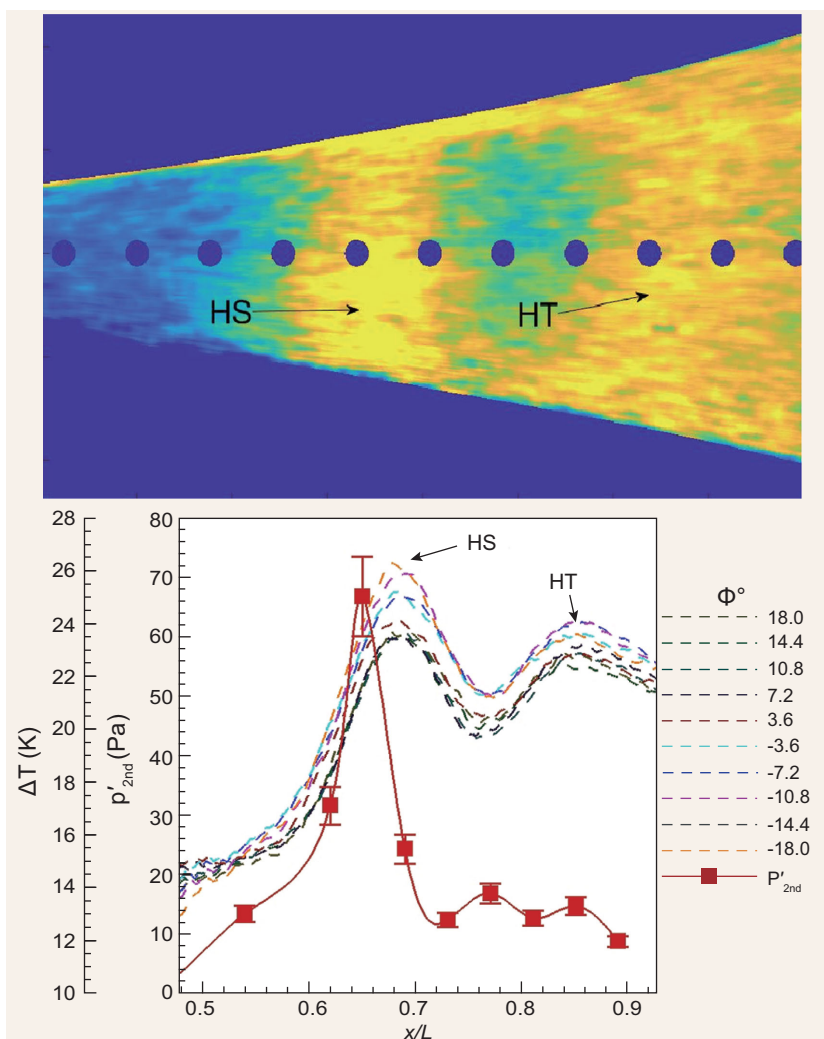


Figure 1. The figures show surface-temperature rise over a flared cone model and the diagram below shows its comparison (dotted lines) with second-mode-instability amplitude (red solid line) in the Mach 6 hypersonic flow. The initial surface temperature is 300 K. The flow in the top picture is from left to right. Blue holes along the centerline represent locations of pressure sensors. HS and HT denote, respectively, the first and second peak of temperature rise. Reproduced from Y. D. Zhu, X. Chen, H. J. Yuan, J. Z. Wu, S. Y. Chen, C. B. Lee, and M. Gad-el-Hak, *Phys Fluids* 2018 30, 011701, with the permission of AIP Publishing. The article can be accessed at <https://doi.org/10.1063/1.5005529>.

reported a new aerodynamic heating mechanism of a high-frequency alternating fluid compression and expansion of second-mode instability, which involved the bulk viscosity of the fluid, in *Physics of Fluids* [2]. This recent research achievement is a major progression in hypersonic transition made by the LTCS [2–5], and provides a new understanding of boundary-layer hypersonic heating phenomena that are vital for the design of hypersonic vehicles, and, therefore, for the realization of hypersonic travel.

Previous work demonstrated that a surface temperature peak (denoted as HS) forms before turbulence sets in, which is followed by rapid growth and then decay (see Fig. 1). A second fast temperature increase (denoted as HT) then occurs at the transition to turbulence. The latter is directly related to the increase of skin friction; however, the former is less understood. The LTCS research team measured the evolution of the second-mode instability amplitude

and found that its peak location is consistent with the first peak of temperature increase. Shear- and dilatation-induced viscous dissipation functions, Φ_ω and Φ_ϑ , are then evaluated based on PIV measurements of the velocity field. This shows that Φ_ϑ mainly contributes to HS, while, downstream of HS, Φ_ϑ decays as the second mode does, but Φ_ω continues to grow. The latter brings about the second growth of surface temperature, HT. Similar phenomena are also observed in PSE and DNS results.

The investigation denotes a new horizon for studies around hypersonic transition. Deviating from the classic Stokes hypothesis, which only considers the shear viscosity, its counterpart, bulk viscosity, has played an important role in energy transfer and dissipation in high-Mach-number flows. An accurate evaluation of bulk viscosity is essential for further theoretical analysis and for the numerical modeling of hypersonic transition.

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REFERENCES

1. Oran ES and Boris JP. *Numerical Simulation of Reactive Flow*. Cambridge: Cambridge University Press, 2005.
2. Zhu YD, Chen X and Yuan HJ *et al. Phys Fluids* 2018; **30**: 011701.
3. Zhang CH, Zhu YD and Chen X *et al. AIP Adv* 2015; **5**: 107137.
4. Zhu YD, Zhang CH and Chen X *et al. AIAA J* 2016; **54**: 3039–49.
5. Chen X, Zhu YD and Lee CB. *J Fluid Mech* 2017; **820**: 693–735.

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