HiSST: 3rd International Conference on High-Speed Vehicle Science Technology

14 -19 April 2024, Busan, Korea

CEAS
Council of European Aerospace Societies

Heat flux increment induced by the coupled shear and compression effects in laminar hypersonic flows

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Abstract

Shear and compression are basic effects in fluid motions. For the new-generation near-space hypersonic vehicles, the flow and heat transfer in the wing-rudder-body interaction region have the characteristics of strong shear and compression simultaneously, resulting in severe local heat flux increment, as a great challenge for thermal protection techniques. A phenomenological decomposition method based on heat transfer mechanisms is proposed, to explain the reason why heat flux is highly increased in these regions. Generalized Rayleigh Flow is established as a theoretical flow model to quantitively illustrate the origin of the heat flux increment. Analytical results for the relative heat flux increment are derived for different angles of attack and the Mach number of freestream. Direct simulation Monte Carlo method is employed to validate the theoretical results. This paper provides a new physical understanding of the aeroheating mechanisms of hypersonic shear-compression flows and is proven to have the potential application value for more complex flows similar to their physical process.

Keywords: *hypersonic, heat transfer, DSMC, boundary layer*

1. Background

On the one hand, from the theoretical point of view, shear and compression widely exist in fluid motions. The Navier-Stokes equations governing viscous and compressible flows contain rich dynamic processes and their interactions [1]. Interpretations of shear and compression within fluid mechanics vary from scholars using different classification criteria: from the kinematics, dynamics, and energy points of view. The first view is based on the decomposition of the velocity field, the Helmholtz decomposition (HD), and is connected with the dynamics point of view through the velocity gradient tensor and Newton's second law of motion, while the description method is based on the third point of view is rarely available in the current literature. While the aeroheating problem is one of the key topics of other engineering and theoretical concern, it is difficult to obtain effective quantitative results using the aforementioned kinematic vector field decomposition methods due to the scalar properties and complexity of the heat transfer process.

On the other hand, from the engineering point of view, take the new-generation hypersonic cruise vehicles as examples, their lifting-body or wave-rider configurations with sharp leading

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edges or nose tips cause the strong shear flow along the streamwise direction in hypersonic speeds [2]. Besides the flaps, wing and rudder are necessary to be used for hypersonic cruise vehicles to acquire maneuverability, while the strong shear flow turns into the strong shear-compression flow in the complex interaction region because of the stagnation effects of the ramp configuration. Thus, the flow and heat transfer in the interaction region have the characteristics of strong shear and strong compression simultaneously. The severe aeroheating caused by such hypersonic strong shear-compression flow is a great challenge for thermal protection techniques. It is still difficult to directly study these flows and heat transfer problems by using any of the theoretical, numerical, or experimental techniques at present.

2. Idea, Method and Results

First, the generalized Rayleigh flow (GRF) established in the former work [3] is used to quantitatively study the relative heat flux increment to illustrate why the heat flux is increased highly in the shear-compression region. GRF, which is a 1D unsteady flow and can be regarded as the flow induced by the sudden motion of an infinite plate with the hypersonic velocity at angle α with itself, is shown in Fig1.a.

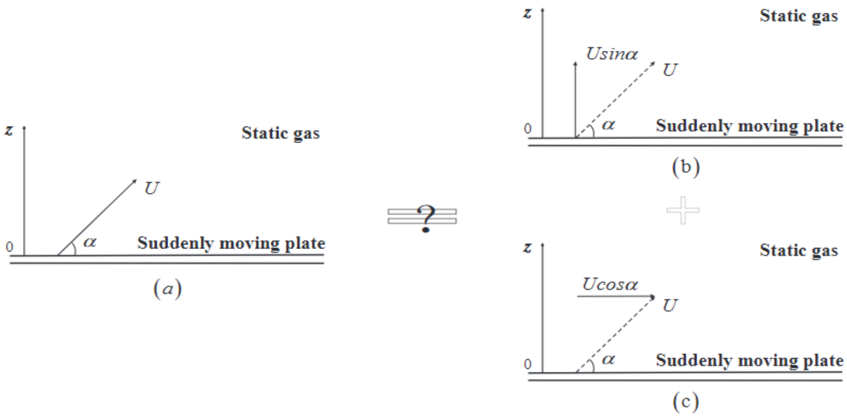

Fig 1. Figure (a), Figure (b), and Figure (c) are schematic diagram for the Generalized Rayleigh Flow (GRF) and its two corresponding elemental models.

Secondly, two different fluid structures are phenomenologically associated to two heat transfer mechanisms: Shock waves caused by momentum stagnation relate to strong compression effects highly raise the temperature and pressure behind it, leading to a heat conduction process. While the boundary layer caused by shear motion of fluid relates to strong shear effects which generates huge viscous dissipation in hypersonic cases, leading to a heat convection process. At the wall, the heated gas near the wall transfers energy to the wall through heat conduction finally. Therefore, two elemental models are divided from the GRF by decomposing its starting speed into perpendicular and parallel components as the counterparts of the compression and shear elemental flow respectively, as shown in Fig 1.b and Fig 1.c.

Finally, when the flow starts long enough ($Re_t \gg 1$), the GRF and its two corresponding elements flows are solved analytically. The angle of the starting speed of GRF, α, is chosen as the parameter to illustrate the relative intensity of compression and shear effects. And by subtracting the sum of the heat fluxes of the two elemental flows from the heat flux of GRF to obtain the coupled incremental heat flux of the two elemental flows. It is found that the incremental heat flux increases with diminishing angle of the starting velocity α. The direct simulation Monte Carlo (DSMC) method [4] is also employed to conduct a series of simulation cases to validate the theoretical modeling results. Fig. 2 shows the incremental heat flux increases with diminishing angle of the starting velocity α.

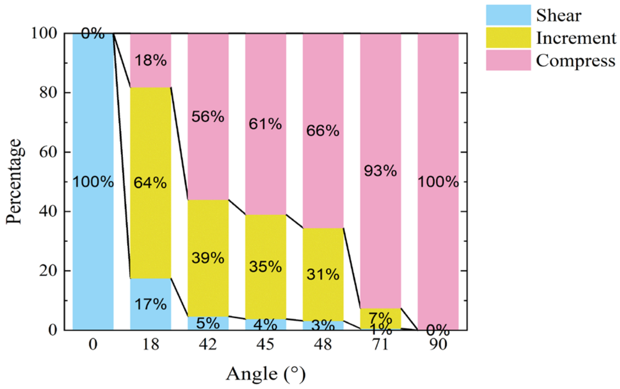

Fig 2. The proportion of heat flux of the two elemental flows corresponding to GRF varies with the angle of the starting velocity of GRF.

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