International Journal of Heat and Mass Transfer 122 (2018) 846–862

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Coupled heat transfer and thermo-mechanical behavior of hypersonic cylindrical leading edges

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ARTICLE INFO

Article history:
Received 21 September 2017
Received in revised form 11 January 2018
Accepted 10 February 2018

Keywords:
Time-adaptive
Thermal response
Structural response
Multi-physics coupling
Leading edge
Hypersonic

ABSTRACT

The analysis of heat transfer and thermo-mechanical behavior is crucial to the leading edge of hypersonic vehicles under high thermal and mechanical loads due to severe aeroheating. The present paper proposes a time-adaptive loosely coupled strategy for the modeling and analysis of hypersonic intrinsic fluid-thermal-structural characteristics. A framework of hypersonic computational coupling dynamics (HyCCD) is developed for integrating an independently developed program solving hypersonic aerothermodynamics and a finite element analysis professional software. The embedded adaptive time-step approach, hybrid interpolation strategy, and grid deformation method have taken into consideration coupling variables and their properties. A typical cylindrical leading edge is considered as the simulation model to study the effects of chemical nonequilibrium, aeroheating duration, flight trajectory, and shock interference. The time-adaptive loosely coupled analysis of aerothermostructural response provides a reliable, applicable and efficient prediction for the fluid thermal-structural coupling of hypersonic vehicles.

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1. Introduction

The hypersonic air-breathing vehicles in the near-space atmosphere experience a sustained long-range maneuverable flight in a wide range of Mach numbers. It makes the aerothermodynamic environment extremely complicated, which is characterized by high-enthalpy flow and long-duration aeroheating flux. There is a physical fact that strong interactions, which are often referred as multi-physics coupling problems, could occur between the external flowfield and the internal structure through a fluid-solid interface. Dechaumphai et al. [1] pointed out that leading edge for hypersonic vehicles experience intense stagnation point pressures and heating rates is often a challenge to the designer. Furthermore, the oblique shock induced by compression surfaces could interfere with the bow shock of leading edge. It results in complex aerothermostructural response to extremely composite loads in a narrow region where the intersected shock impinges on the surface. This shock-interference heating becomes a critical problem in the prediction and design of the thermal protection system (TPS) and hypersonic vehicles.

Many efforts have been made to improve the understanding the complex flow pattern of shock interference and severe heating. Edney [2] essentially classified the shock interference patterns into six types according to the location of the intersection point between the impinging shock and the bow shock. Wieting groups [3–6] initiated a unified set of experiments to provide pressure and heat transfer rates on a cylindrical leading edge for the design of hypersonic inlet cowl. They extended the experimental researches on the effects of Mach numbers from 8 to 19 and leading-edge sweep and even studied the shock wave interference pattern of dual incident oblique shock waves intersecting the bow shock wave of a cylinder. However, the experiments only simulate flight conditions with the maximum test time of 120 ms limited to the capability of shock tunnels. The short run times can hardly response the coupled characteristics in shock interference regions.

Apart from the analytical and experimental studies, this problem has received considerable attention for computational studies through the development of compressible flow solvers [7,8] and understanding of interaction dynamics [9,10]. Chen et al. [11] studied the effect of blunt radii of the leading edge for waveriders on the reduction of the maximum heat flux based on numerical simulations. Liu et al. [12] studied the effects of attack angle and sideslip angle on the aero-heating characteristics of nose region and leading edge for TPS design of blunted waverider. Zhu et al.

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[1] *Abbreviations:* AECC, Aero Engine Corporation of China; Co., Ltd. Company Limited.

https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.037
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[13] investigated thermal and mechanical performances of leading edge with active-cooled impingement jet by a quasi-coupling method. Soloveichik et al. [14] studied the thermo-mechanical behavior of composite made nose caps at different non-zero angles of attack with high time-variable thermal and mechanical loads during the flight of the hypersonic vehicle. It could be found that sustained hypersonic flight conditions make it a highly coupled problem involving the composite effects and their interactions.

For practical engineering applications, it is crucial to predicting the interdisciplinary coupling and interaction based on fluid-thermal-structural coupling strategies. Though aerothermal characteristics of leading edge have been studied intensely, less attention is paid to the aerothermostructural response and the effects of sustained and complex flight conditions, especially shock interference. In order to improve computationally feasibility with high-fidelity modeling techniques and minimize computational expense, the present work develops a time-marching simulation framework of hypersonic computational coupling dynamics (HyCCD). It has embedded the time-adaptive, loosely coupled strategy, which was demonstrated credible and efficient in a previous study [15]. To the knowledge of the authors, the time adaptivity in the context of aerorthermostructural problems has been rarely investigated yet. The present work further focuses on the effects of chemical nonequilibrium, aeroheating duration, flight trajectory, and shock interference on a cylindrical leading edge. The purpose is to gain an insight into its distinctive fluid-thermal-structural features, and the numerical results are expected to provide technical support to the effectiveness of TPS system and safe design of hypersonic vehicles.

2. Description of leading edge model

For the airframe/engine integrated design of new-generation air-breathing hypersonic vehicles, the forebody is utilized to produce lift by pre-compression. The leading edge of fuselage nose, wing, fuel strut and the cowl on the windward side will endure severe aeroheating environment. Especially, during the actual flight of hypersonic vehicle, when the flight speed reaches the engine operating condition, as shown in Fig. 1 (left), the inlet cowl will open, and the inlet starts to capture the flow into the engine. The shock interactions and their complex flow pattern will produce transient shock interference heating, which results in a significant amplification of the heating rate on the leading edge under the composite flight conditions. By simplifying the practical model into Fig. 1 (right), a cylindrical leading edge model [16] is considered for validating the time-adaptive loosely-coupled analysis for the fluid-thermal-structural problems in hypersonic flows. It is also used to study aerothermostructural response subjected to sustained aeroheating and shock interference aeroheating.

According to the impingement location of induced oblique shock on the cowl lip, the shock interactions can be classified into three categories in Fig. 1. When the incident shock wave crosses the cowl lip and enters the inlet, Condition I is defined as a supercritical state in which the leading edge is under far-field freestream condition. When the incident shock impinges right on the cowl lip and interferes with the bow shock of leading edge, Condition II is a critical state. When the incident shock passes outboard of the cowl leading edge, Condition III is defined as a subcritical state, in which the cowl leading edge is exposed to the flow conditions behind the induced shock wave. The present work focuses on Condition II, which is the regional distribution of Condition I and Condition III. The shock interactions may lead to several times higher heating rate in the shock impingement area than that of uniform flight conditions, even more, severe than the stagnation point of leading edge.

3. Time-adaptive loosely coupled strategy

Multi-physics coupling problem mainly involves a complex physical process between aerothermodynamics in fluid and thermo-structural dynamics in solid through a fluid-solid coupling interface. Its modeling and analysis can generally be divided into monolithic coupling approach and the partitioned coupling approach [17,18]. According to the coupling characteristics, the fluid-thermal-structural coupling model is shown in Fig. 2. It represents a strong two-way coupling relationship between the aerothermodynamic environment of external flowfield and the structural thermal response of internal solid structures.

The volumetric coupling of aerodynamic forces and aeroheating fluxes in fluid is described by governing equations of aerodynamic flow, which is solved by computational fluid dynamics (CFD) to obtain the parameters of aerothermodynamic loads. The thermal load (wall heat flux q) and aerodynamic force load (wall pressure p) are imposed on the solid through fluid-solid coupling interface. The structural thermal response in solid is described by governing equations of structural heat transfer and thermoelastics, which is solved by finite element method (FEM) to obtain structural/thermal coupling parameters. The temperature condition (wall temperature T) and structural deformation condition (surface displacement $\mathbf{u}$) are provided for the fluid through fluid-solid coupling interface to take into account the effects of temperature-deformation coupling.

When the vehicle flies at a hypersonic speed within the atmosphere, the aerothermodynamic loads as active excitation changes continuously along the flight trajectory so that the fluid-thermal-structural coupling problem appears as a sustained physical coupling process. Two concepts are introduced herein: (1) static flight trajectory, which refers to the flight state (height, speed, and angle of attack) remaining constant with time; (2) dynamic flight trajectory, which refers to the flight state (height, speed, and angle of attack) varying continuously with time. It involves three obviously different characteristic times of the flight trajectory, the flow response and the structural thermal response, which should be taken full account in the coupling analysis strategy.

The flow response characteristic time can be expressed as follows:

$$\tau_F = \frac{L}{U_\infty} \tag{1}$$

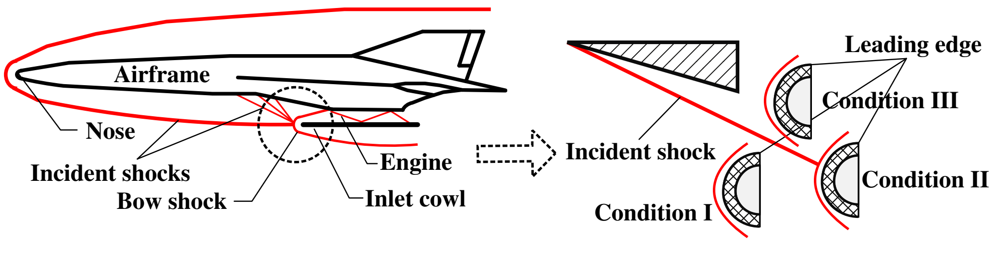

Fig. 1. Shock interaction phenomena near leading edges of hypersonic vehicles.

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