Commun. Comput. Phys.
doi: 10.4208/cicp.OA-2020-0042

Vol. **29**, No. 3, pp. 853-904
March 2021

Multiple-Temperature Gas-Kinetic Scheme for Type IV Shock/Shock Interaction

Hualin Liu[1], Guiyu Cao[2] and Weifang Chen[1,2,*]

[1] *College of Aeronautics and Astronautics, Zhejiang University, Hangzhou 310027, China.*
[2] *Department of Mathematics, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong.*

Received 27 February 2020; Accepted (in revised version) 17 June 2020

Abstract. In this paper, a gas-kinetic scheme (GKS) method coupled with a three temperature kinetic model is presented and applied in numerical study of the Edney-type IV shock/shock interaction which could cause serious problems in hypersonic vehicles. The results showed very good agreement with the experimental data in predicting the heat flux on the surface. It could be obviously seen that the current method can accurately describe the position and features of supersonic jets structure and clearly capture the thermal non-equilibrium in this case. The three temperature kinetic model includes three different models of temperatures which are translational, rotational and vibrational temperatures. The thermal non-equilibrium model is used to better simulate the aerodynamic and thermodynamic phenomenon. Current results were compared with the experimental data, computational fluid dynamics (CFD) results, and the Direct Simulation Monte Carlo (DSMC) results. Other CFD methods include the original GKS method without considering thermal non-equilibrium, the GKS method with a two temperature kinetic model and the Navier-Stokes equations with a three temperature kinetic model, which is the same as the multiple temperature kinetic model in current GKS method. Comparisons were made for the surface heat flux, pressure loads, Mach number contours and flow field values, including rotational temperature and density. By Comparing with other CFD method, the current GKS method showed a lot of improvement in predicting the magnitude and position of heat flux peak on the surface. This demonstrated the good potential of the current GKS method in solving thermodynamic non-equilibrium problems in hypersonic flows. The good performance of predicting the heat flux could bring a lot of benefit for the designing of the thermal protection system (TPS) for the hypersonic vehicles. By comparing with the original GKS method and the two temperature kinetic model, the three temperature kinetic model showed its importance and accuracy in this case.

*Corresponding author. *Email addresses:* hualinliu@zju.edu.cn (H. Liu), gcaoaa@connect.ust.hk (G. Cao), chenwfnudt@163.com (W. Chen)

AMS subject classifications: 76-XX, 65-XX

Key words: Gas-kinetic scheme, multiple temperature kinetic model, hypersonic, shock/shock interaction, thermodynamic non-equilibrium.

1 Introduction

For more than half a century after the German scientists Euger Sanger and Irene Bredt proposed the concept of intercontinental hypersonic missiles in the 1940s, hypersonic [4] has been a popular and important research subject for both of the civilian and military use [18, 56]. Military weapon systems could benefit from the superior speed, longer range, effective penetration of the defense system, and mission flexibility using hypersonic technique. The hypersonic technique can also be used in civilian applications for commercial transportation within the atmosphere such as a hypersonic plane or access from earth to orbit transportation through the atmosphere such as the Crew Transport Vehicle (CTV) and Crew Exploration Vehicle (CEV) [26]. In less than an hour, a hypersonic plane can carry around twenty tons of cargo or several hundreds of passengers from New York to London [72]. And the CTV and CEV are designed to replace the space shuttle because of its high efficiency and safety [2].

The leader of the American Air Force once detailed a 30-year plan for five so-called game-changing technologies for the future [72]. Hypersonic technology was the first one among the five technologies.

In the last two decades, a number of hypersonic programs have been built by industries working together with scientific organizations around the world. Some famous projects are listed here as:

- **HIFiRE**: the Hypersonic International Flight Research and experiment program [36, 84].
- **STAR**: the stability Analysis for Reentry including HTV-2 and X-51 [43, 85].
- **NHFRP**: the National Hypersonic Foundational Research Plan [70].

However, these and other hypersonic projects still remain far from the full potential of hypersonic capability. For example, both two HTV-2 flights ended in failure. The first flight lost connection with the ground about nine minutes after launch, and the second flight lost connection about 30 minutes after launch. The U.S. Navy HyFly [61] project conducted three attempts, none of them successfully reached to a hypersonic speed. Even the X-51 supported by DARPA [43] showed only a 25 percent success rate among all four flight tests. Though not desirable, these failures are predictable because of the significant gaps in our basic knowledge of designing a hypersonic vehicle [9]. There're several issues preventing researchers from fully success to a hypersonic vehicle, including: