Commun. Comput. Phys.
doi: 10.4208/cicp.OA-2016-0221

Vol. **23**, No. 4, pp. 1094-1115
April 2018

Further Investigation on the Flow and Heat Transfer Mechanism of Single-Jet Film Cooling Based on Hybrid Thermal Lattice Boltzmann Method

Yanqin Shangguan, Xian Wang*, Hu Zhang and Yueming Li

State Key Laboratory for Strength and Vibration of Mechanical Structures, Shaanxi Key Laboratory of Environment and Control for Flight Vehicle, School of Aerospace, Xi'an Jiaotong University, 28 Xianning West Road, Xi'an 710049, Shaanxi, China.

Received 25 November 2016; Accepted (in revised version) 12 April 2017

Abstract. Massively parallel simulation applied multiple graphic processing units (multi-GPUs) is carried out to perform an in-depth investigation on the flow and heat transfer mechanism in film cooling based on hybrid thermal lattice Boltzmann method (HTLBM). For the flow field, multiple-relaxation-time (MRT) collision model is used. A coolant jet is injected at an inclined angle of $\alpha=30^\circ$ into a turbulent flat plate boundary layer profile with free-stream Reynolds number of $Re=4000$. In our previous work [1], we proposed a three-part definition for the jet-crossflow-interaction region according to the turbulent kinetic energy (TKE) distribution and the unsteady mixing characteristics in each domain were studied qualitatively. In order to further investigate this phenomenon, a more detailed study on unsteady flow and heat transfer characteristics is performed in this work. The results show that the shear domain is dominated by the shearing effect and covered by stable coolant film. In rotating domain, the turbulent intensity increases because of the violent mixing between crossflow and jet flow and the coolant film begins to spread in lateral. All of these cause the rapid decrease in coolant film stability. The great turbulent-dissipation effect in dissipation domain weakens the turbulent intensity and strengthens the fluctuation of spanwise velocity. The cooling performance is very poor.

AMS subject classifications: 76F65

Key words: Hybrid thermal lattice Boltzmann method, multiple-relaxation-time collision model, multiple graphic processing units, film cooling, mixing mechanism.

*Corresponding author. *Email addresses:* `sgyq.6510336@stu.xjtu.edu.cn` (Y. Q. Shangguan), `wangxian@mail.xjtu.edu.cn` (X. Wang), `huzhang@xjtu.edu.cn` (H. Zhang), `liyueming@mail.xjtu.edu.cn` (Y. M. Li)

1 Introduction

Increasing the inlet temperature has become one of the trends in advancing modern gas turbine technology to improve its output and efficiency. Since inlet temperature has exceeded the allowable material temperature, thermal barrier coating (TBC) and film cooling are used in conjunction with increased inlet temperature of gas turbine. Film cooling, as one of the most important cooling methods, is extensively applied to reduce the surface temperature of components. The film-cooling mixing mechanism is highly complex and the performance of film cooling is affected by so many factors. Therefore, the detailed understanding of the mixing mechanism between hot crossflow and coolant jet is necessary to effectively design aerodynamic and structure parameters in film cooling.

Over the last three decades, film cooling has been widely studied. Plenty of them focused on geometries and flowing parameters influencing film cooling performance [2]. An extensive study on the effect of the density ratio was presented by Goldstein et al. [3]. Andreopoulus and Rodi [4] measured the flow field at different velocity ratios using hot-wire probes. An LES study that includes an accurate treatment of the incoming turbulent boundary layer and a plenum area was performed by Guo et al. [5], who investigated the effects of the inclination angle and blowing ratio on the flow field. The effect of film-hole geometry and angle on turbine blade leading edge film cooling has been experimentally studied by Gao and Han [6]. Qin et al. [7] studied compound angle film cooling effectiveness with streamwise pressure gradient and surface curvature effects using pressure sensitive paint (PSP) technology. However, in-depth studies on mixing mechanism of film cooling remain sparse.

As for the investigation on the mixing mechanism of film cooling, numerical simulation with high resolution is indispensable, as large-scaled simulations allow detailed examination of quantities which are difficult to measure accurately in experiments. Moreover, due to the limitation of central processing unit (CPU), the relatively fine results could not be obtained by the previous computations with restricted computational grid number. Acharya and Leedom [8] carried out numerical simulations to study the effect of plenum inflow orientation on cooling performance with about 5.15 million grids and just obtained the general agreement between the calculated and film cooling effectiveness and test results. Renze et al. [9] investigated the impact of the velocity and density ratio on the turbulent mixing process in gas turbine blade film cooling with 5.65 million grids. There was still a difference between the measured results and numerical results. The results LES of leading edge film cooling was conducted by Rozati and Tafti [10] with about 9.6 million grids to analyze the flow structures, effectiveness and heat transfer coefficient. The results shown in [10] did not present the very fine flow and heat characteristics in film cooling process. In 2013, Andrew et al. [11] performed a blind LES of film-cooling with 88.7 million meshes. This is by far the most massive computational grid system in our minds and it was run on 256 processors (8 nodes of quad-processor eight-core 2.0 GHz AMD Opteron 6128), 512GB ram and a 20Gb/s infiniband interconnect. The results of spanwise-averaged film cooling effectiveness still showed a discrepancy between the nu-