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Research Paper

A new wall function boundary condition including heat release effect for supersonic combustion flows

Zhen-Xun Gao, Chong-Wen Jiang *, Chun-Hian Lee

National Laboratory for Computational Fluid Dynamics, School of Aeronautic Science & Engineering, Beihang University, Beijing 100191, China

HIGHLIGHTS

- A new wall function including heat release effect is theoretically derived.
- The new wall function is a unified form holding for flows with/without combustion.
- The new wall function shows good results for a supersonic combustion case.

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ABSTRACT

A new wall function boundary condition considering combustion heat release effect (denoted as CWFBC) is proposed, for efficient predictions of skin friction and heat transfer in supersonic combustion flows. Based on a standard flow model including boundary-layer combustion, the Shvab–Zeldovich coupling parameters are introduced to derive a new velocity law-of-the-wall including the influence of combustion. For the temperature law-of-the-wall, it is proposed to use the enthalpy–velocity relation, instead of the Crocco–Busemann equation, to eliminate explicit influence of chemical reactions. The obtained velocity and temperature law-of-the-walls constitute the CWFBC, which is a unified form simultaneously holding for single-species, multi-species mixing and multi-species reactive flows. The subsequent numerical simulations using this CWFBC on an experimental case indicate that the CWFBC could accurately reflect the influences on the skin friction and heat transfer by the chemical reactions and heat release, and show large improvements compared to previous WFBC. Moreover, the CWFBC can give accurate skin friction and heat flux for a coarse mesh with y^+ up to 200 for the experimental case, except for slightly larger discrepancy of the wall heat flux around ignition position.

1. Introduction

Accurate predictions for the skin friction and heat transfer inside a scramjet engine are a big challenge to the computational fluid dynamics (CFD) technique [1,2]. The velocity and temperature take on sharp variations near the wall for a turbulent boundary layer in supersonic combustion flows, caused by the viscous effect or the combustion heat release. It is pointed out by Refs. 3–5 that when using Reynolds-averaged Navier–Stokes (RANS) simulations to resolve the whole turbulent boundary layer, it is necessary for the distance of the first grid point off the wall, Δy, to satisfy the relation $y^+ = \rho_w u_\tau \Delta y / \mu_w < 1$ so as to correctly calculate the gradient of velocity and temperature at the wall. However, to satisfy $y^+ < 1$, Δy needs to be very small, which is generally 10^{-6} m or even smaller. For a simulation of complicated scramjet engine, so dense grid points near the wall would greatly limit the integration time step, and meanwhile, the sophisticated chemical reactions could also take huge computation time to simulate. Then, the computational consumption might be too enormous to be acceptable. One way to alleviate this difficulty is to use a wall function boundary condition (WFBC), which does not resolve the near-wall region of the turbulent boundary layer while straightly uses velocity and temperature law-of-the-walls to represent their distributions in the near-wall region and obtains the skin friction and heat transfer indirectly. The utilization of WFBC can relax the restriction of the density for near-wall grid points and meanwhile reduce the grid-dependence of the predictions for skin friction and heat transfer. Also, this WFBC method is often adopted in large eddy simulation (LES) to avoid the intricate near-wall treatments [6,7].

However, the complexity of the flow inside a scramjet engine causes additional difficulties for the WFBC application. On one hand, the supersonic characteristic and wall cooling process require that compressibility and heat transfer effects should be included in WFBC. On the other hand, the chemical reactions may take place inside

* Corresponding author. Tel.: +86 1082315396; fax: +86 1082315396.
E-mail address: cwjiang@buaa.edu.cn (C.-W. Jiang).

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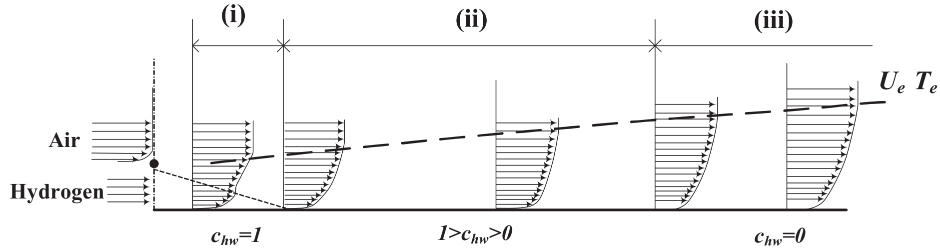

Fig. 1. Standard flow model including boundary-layer combustion.

the turbulent boundary layer and the resultant heat release could largely influence the turbulence structure [8,9], then leading to variations of the skin friction and heat transfer. Therefore, the heat release effect inside a boundary layer should also be considered in a WFBC toward scramjet engine applications.

Most of the available compressible wall functions are direct extensions from the incompressible forms just by considering the variation of mean density [10–12]. To take the compressibility and heat transfer effects into account, Nichols et al. [3] presented a new WFBC in 2004, in which White's compressible velocity logarithmic law [13] and the Crocco–Busemann equation [14] are introduced, respectively. Afterwards, this WFBC was adopted in some simulations of skin friction and heat transfer for compressible boundary layers [15,16]. Moreover, Gao et al. presented further modifications [17] on Nichols' WFBC to enhance its accuracy for different types of supersonic flows.

However, to the authors' knowledge, all of the existing WFBCs are established based on the assumption that there is no chemical reaction taking place inside the boundary layer. Therefore, all the available WFBCs cannot be directly used in supersonic combustion flows inside a scramjet engine, where chemical reactions are likely to occur inside the boundary layer. Stalker and his colleagues conducted a series of experiments to study the influences of combustion taking place inside a supersonic turbulent boundary layer [18–20]. It was revealed that the heat release effect from hydrogen/air combustion could reduce the local skin friction about 70%–80% [18,19]. Moreover, Gao et al. [21] performed numerically parametric studies on this boundary-layer combustion flow and found that while the combustion flame front is restricted around the edge of boundary layer, the heat release does not increase the wall heat transfer, but as the flame front moves toward the wall, the heat transfer would be dramatically enhanced. In summary, the combustion heat release inside a supersonic boundary layer could largely change the results of the skin friction and heat transfer. Hence, if a WFBC not considering heat release effect is adopted to simulate flows in scramjet engines, large errors might be introduced to the skin friction and heat transfer.

The objective of this paper is to develop a WFBC, for the first time, that can be used in supersonic combustion flows for efficient predictions of skin friction and heat transfer. This new model will be denoted as CWFBC, where the first letter 'C' represents combustion. In Section 2, theoretical analysis is performed on a standard flow model, to obtain analytical expressions of the velocity and temperature law-of-the-walls for a supersonic turbulent boundary layer with chemical reactions and heat release. Then, the CWFBC is established based on the velocity and temperature law-of-the-walls. In Section 3, numerical experiments are performed to validate the reliability of the proposed CWFBC in detail.

2. Establishment of CWFBC

The velocity and temperature law-of-the-walls are the most important parts in a WFBC. Therefore, in order to establish the CWFBC, the formulas of velocity and temperature law-of-the-walls must be modified to include the heat release effect. In the following, a stand flow model is first described, and then theoretical derivations are carried out to obtain the velocity and temperature law-of-the-walls considering heat release effect.

2.1. Standard flow model

The standard flow model adopted in the present research is shown in Fig. 1, which is originally designed by Stalker [22]. This flow model is a flat-plate supersonic boundary layer flow including hydrogen injection and diffusion combustion. Hydrogen is injected parallel to the wall from a slot with a certain height, and then the flow experiences several different regions in the process of its downstream development, regions (i), (ii) and (iii), as marked in Fig. 1. Similar to Stalker's study in Ref. 22, region (ii), which manifests the heat release effect in supersonic turbulent boundary layers, is the focus of the present research.

In order to make the following theoretical analysis feasible, region (ii) is physically substituted by an ideal model [22] shown in Fig. 2. It is assumed that region (ii) starts from the leading edge of the flat plate, and then a diffusion gradient of hydrogen from the wall toward a flame front inside the boundary layer is set up. Hydrogen is continuously injected along the wall so that c_{hw} maintains a constant value. Stalker [22] argued that the substituted model in Fig. 2 can be related piecewise to region (ii) in Fig. 1 by using local similarity, and the key parameter for this connection is just c_{hw}. Moreover,

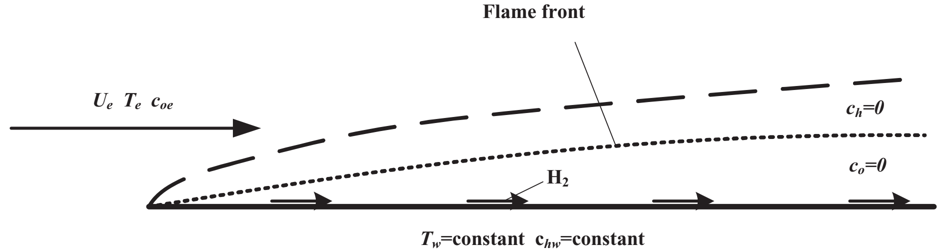

Fig. 2. Substituted model for the standard flow model.