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Unsteady Heat and Mass Transfer of a Blunt Leading Edge using Hybrid LES-RANS

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Abstract A novel wall-proximity based hybrid LES-RANS approach has been applied for the study of a blunt leading edge flat plate with constant wall heat flux. The Reynolds number of the flow is about 10,200 based on half of the plate thickness. Results of the simulation are examined by comparing the velocity and heat transfer profiles with relevant measurements. Analysis has been carried out to study the relation between the unsteady flow features and the surface heat transfer.

Keywords: Heat transfer, Blunt flat plate, Hybrid LES-RANS, Proper orthogonal decomposition

1. Introduction

Heat transfer and its mechanisms in separated and reattched flows have been experimentally studied since the middle of the 20th century. Curiosity has been driven by improving industrial applications such as heat exchangers, cooling channels, gas turbine components and nuclear reactors. The continuing improvements of computational resources is allowing use of higher fidelity methods over RANS approaches. Although LES may still be a research tool, hybrid LES-RANS methods may act as a step in-between for industrial uses. A review of the relevant work, both experimental and numerical, on the blunt flat plate heat transfer can be found in [1].

In this work, a novel hybrid LES-RANS approach is used. The RANS and LES regions are defined by a modification of the nearest wall distance $\tilde{d}$ as Fig. 1 shows. The modified wall distance $\tilde{d}$ is defined as,

$$\tilde{d} = \left[1 - \tanh(\alpha \frac{d - d_c}{d_c})\right] \frac{d}{2}$$

where $\alpha$ is a control parameter for the decay rate of $\tilde{d}$ in the mixed zone, $d_c$ is the RANS cut-off distance typically at $y^+ \approx 60$. In addition, $\varepsilon = \tanh[\beta(d - \tilde{d})]$ is the weighting parameter for LES if an explicit SGS model is used, where $\beta$ is the control parameter for the growth rate of $\varepsilon$ in the mixed zone. A smooth transition in the eddy viscosity field is therefore obtained and helps maintain good numerical stability. No explicit SGS model is used ($\varepsilon = 0$) in the present study, which is often referred to as implicit or numerical LES. This hybrid LES-RANS approach has been successfully applied to the heat transfer study of a square cylinder in crossflow [2].

The investigated plate is $2H$ thick, $40H$ long and $10H$ wide, while $H = 10 \text{ mm}$. This geometry is coherent with the experiments of Ota and Kon [3]. A sketch of the computational domain is presented in Fig. 2. Conditions at the inlet are set to $P_\infty = 101,325 \text{ Pa}$, $U_\infty = 16 \text{ m/s}$ and $T_\infty = 300 \text{ K}$. Reynolds number of the flow is $Re_H = 10,200$. At the plate surface, a no-slip condition and a constant heat flux density condition are used.

2. Preliminary results

Validation of the flow field is performed by comparing the velocity profiles with available measurements as presented in Fig. 3 (a). The at locations are scaled based on the reattachment length. A good agreement is reached between the simulation results and the measurements.
Small underestimation occurs inside the recirculation region ($x = 0.5Lr$). This suggests that the velocity recovers slower in the upper shear layer compared to the experiment.

Heat transfer results are assessed by the averaged surface Nusselt number and non-dimensional temperature profiles. Fig. 3 (b) illustrates the non-dimensional temperature profiles at selected downstream positions. The non-dimensional temperature profiles compare well against the measurements, despite very small underestimation close to the wall in the recirculation region ($x < 1.0Lr$).

Examination of the major flow features is carried out by the $\lambda_2$ criterion, Reynolds stress profiles and spectrum analysis. The shear layer, separation bubbles and hairpin structures are visualised in Fig. 4. Proper Orthogonal Decomposition (POD) is applied to the velocity field as well as the surface temperature field to identify the most energetic structures that affect the surface heat transfer as Fig. 5 illustrated. Fig. 6 (a) presents the unsteady structures and temperature side-by-side, and Fig. 6 (b) shows a schematic of the vortices that are closely related to the surface heat transfer. These structures and their effect on the surface heat transfer will be studied.

References

Fig. 1. Blending of RANS and LES regions
Fig. 2. Sketch of the computational domain
Fig. 3. Spanwise averaged profiles of (a) velocity and (b) temperature, Hybrid LES-RANS, ○ Ota and Kon [3]
Fig. 4. Visualisation of the separated and reattached flow by isosurfaces of $\lambda_2$
Fig. 5. POD analysis of the surface temperature: (a) energy fraction of modes, (b) reconstructed temperature field from the 1st mode
Fig. 6. (a) Visualisation of vortices adjacent to the wall temperature of a snapshot in time and (b) schematic of unsteady features that affect surface heat transfer