HEAT TRANSFER MECHANISMS IN SEPARATED TURBULENT FLOWS

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ABSTRACT

This study aims to gain insights into the underlying mechanism of heat transfer characteristics in separated flows using a reduction model through Dynamic Mode Decomposition Reduced-Order Models. To this end, highly resolved Large Eddy Simulations (LES) are performed to explore the effect of wall thermal conditions on the behavior of a separated flow on a flat surface. Various wall-to-recovery temperature ratios and an adiabatic surface will be considered. Next, we use the dynamic mode decomposition (DMD) to identify the structures generated by the shear layer and the exposed bluntness. This modal decomposition analysis will be deployed here to contribute to a better understanding of the interrelated mechanisms between eddy structures and wall pressure fluctuations. Therefore, a thorough understanding of heat transfer effects on turbulence structures near the wall will be achieved.

Introduction

Separated flows have engineering concerns since they can occur in many aerodynamic applications. Examples include separated flow around ground vehicles, trains, or aircraft bodies. Controlled separation, however, may be advantageous as in the case of slender delta wings, spoilers used on wings for control purposes and transverse fins used to improve the heat transfer performance of nuclear reactor fuel elements.

There are two significant challenges associate with the unsteady behavior of separated flows. Mechanisms driving the acoustic propagation in the far-field surrounding these aerodynamic bodies can impact the system's structural integrity. Another one is the sound propagation toward the vehicle's interior, which has the same range of frequencies as voice. Therefore a thorough understanding of mechanisms underlying the acoustic and noise generations and their transmissions are essential for designing of controlling acoustic disturbances and developing noise reduction process techniques. On the other hand, separation of flow may be used as a means of controlling the heat transfer to a surface and for aerodynamic control purposes. Heat-transfer characteristics of separated flows are of considerable interest in the design of heat exchangers, aircraft and space vehicles.

A mechanistic understanding of interrelated mechanisms that couples heat transfer and flow unsteadiness in separated flows leads to engineering advanced control systems for separated and attached boundary layers that are solutions for noise reduction techniques and surface heat transfer controlling.

Since the source noise is essentially the coupling between turbulence structures and the unsteady pressure field in the core of the flow, previous studies were devoted to accurately predicting the pressure fluctuations generated within the flow that is central to the acoustic source generation along the solid surfaces. Wall pressure fluctuations are related to the motion of large-scale vortices, especially hairpin vortices in the reattachment region that produce large amplitude fluctuations (Figure 1). Two main mechanisms govern the flow in the unsteadiness in the separation bubble: the shedding of large-scale vortices downstream of the separation and a low-frequency unsteadiness called flapping, linked to the shredding and enlargement of the bubble. These two mechanisms also can couple; however, the connection is still not clear.

Several works discussed the existence of vortex shedding and low frequency shear layer flapping in separated flows (Tenaud *et al.* (2016)). Previous simulations are devoted to describing better the relationship between pressure fluctuations and vortex dynamics for separated-reattached flow over a flat plate (Minsuk & Wang (2010)). However, all these studies addressed the case of adiabatic wall conditions, and to our knowledge, no high-fidelity simulations have been carried out to explore heat transfer mechanisms in unsteady separated flows.

Results

The separated–reattached turbulent flow over a blunt, flat plate with a right-angled leading edge is the subject of this study. It is equipped with a right-angled corner leading-edge. This flat plate spans the computational domain horizontally in its centerline, as seen in Fig 1. The inlet boundary is located $10H$ upstream of the sharp leading edge to minimize its influence on the uniform inlet boundary condition. The flat plate has a streamwise length of $25H$, extending up to the streamwise outlet boundary. The computational domain sizes we retained to analyze LES results are $L_x = 35H$ in the streamwise direction, $L_y = 5H$ in the spanwise direction and $L_z = 17H$ in the normal to the flat plate direction. These domain sizes provide with blockage ratio that are equivalent to previous studiesTenaud *et al.* (2016).

Numerical predictions using Large-eddy simulation (LES) will provide the base data for the dynamical analysis in this study. We solve the filtered compressible Navier–Stokes equations following an LES approach with k-equation subgrid model (Chai & Mahesh (2012)).

Simulations will be carried out at various values of the wall-to-recovery-temperature ratio, representing cooled, adiabatic, and heated walls as shown in Table 1.

An in-house finite-volume code will be used to carry out LES. The flow is assumed as Newtonian with a specific heat ratio and Prandtl number of $\gamma = 1.4$ and $Pr = 0.72$, respectively. A detailed comparison of the present LES and experimental

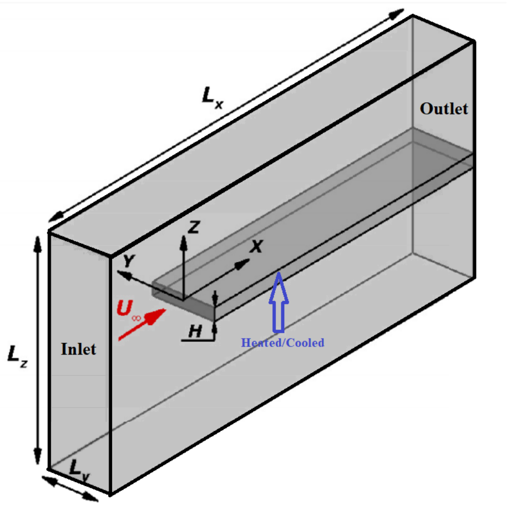

Figure 1. Simulation Domain

Table 1. Flow parameters for LES simulations.

Test case	Re_H	$T_\infty(K)$	$T_w(K)$	$\delta_s(mm)$
Cooled	7500	300	290	3
Adiabatic	7500	300	300	3
Heated	7500	300	330	3

results for the reattaching free shear layer, including the reattachment process and downstream boundary layer growth, was previously published by the author (Zangeneh (2020*a*, 2021, 2020*b*, 2021 doi=10.1115/1.4048611)).

Next, we use the Dynamic Mode Decomposition (DMD) to identify the structures generated by the shear layer and the exposed bluntness. We will use the DMD method proposed by Schmid (Schmid & Peter (2010)). The method provides a set of non-orthogonal modes, each having a characteristic frequency. The temporal and spatial variations are therefore fully coupled.

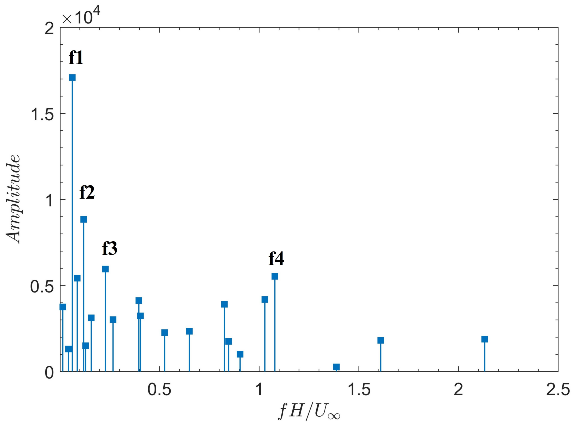

Figure 2. Amplitudes of difference modes for adiabatic wall.

DMD approach assumes a series of N time snapshots of the velocity field separated by Δt, $X_1^N = \{v_1, v_2, ..., v_N\}$ (Hemati *et al.* (2017)). When applied to a linear system, the equation is exact. In this case, the computed modes/eigenvalues represent the physically correct structures and their growth rates, frequencies. For non-linear systems, it represents a best linear map that links all snapshots. If the flow is characterized by periodically repeatable and persistent (i.e., neutrally stable) structures, the DMD method should be able to detect these and the associated frequencies. This modal decomposition analysis is proposed here to contribute to a better understanding of the interrelated mechanisms between eddy structures and wall pressure fluctuations. Therefore, a thorough understanding of heat transfer effects on turbulence structures near the wall will be achieved.

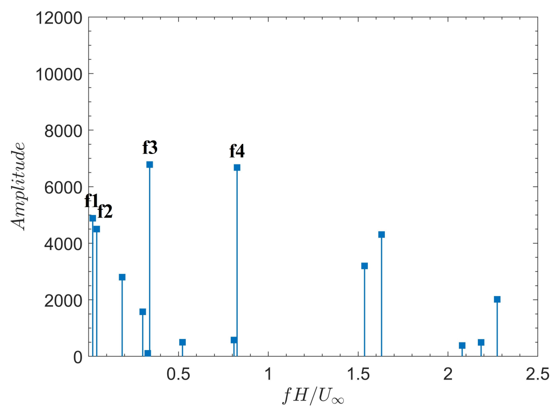

Figure 3. Amplitudes of difference modes for cooled wall.

Figure 2 shows the dominant frequencies, one at the frequency of $f_1H/U_\infty = 0.06$, another at a frequency of $f_2H/U_\infty = 0.12$, still another at the frequency of $f_3H/U_\infty = 0.23$, and a distant peak at the frequency of $f_4H/U_\infty = 1.1$. The first three frequencies were also educed through a DMD decomposition applied on the same configuration (Debesse et al., 2016). It can be attributed to the Kelvin–Helmholtz mode of the mixing layer edging the separation since $f4$ matches the Strouhal number of the Kelvin–Helmholtz frequency recorded experimentally by numerous authors.

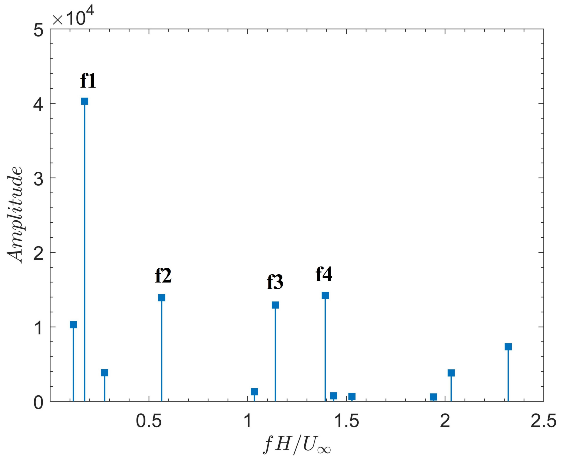

Figure 4. Amplitudes of difference modes for heated wall.

Separated–reattached flows are characterized by two frequency modes which are related to shedding and flapping phenomena. The vortex shedding resulting from the large scale motion of the mixing layer, is characterized by a frequency peak band around $fL/U_\infty = 0.6$ - 0.8 (corresponding to the shedding modes, $f_1H/U_\infty = 0.11$ - 0.14) (Cherry et al., 1984; Kiya and Sasaki, 1983, 1985). The flapping phenomenon is an overall dynamical mechanism linked to successive enlargements and shrinkage of the separated zone. Its characteristic frequencies (corresponding to the flapping modes) are much lower than those of the shedding modes, e.g. $fL/U_\infty = 0.12$ ($fH/U_\infty = 0.024$) (Cherry et al., 1984; Kiya and Sasaki, 1983; 1985). The two lowest frequencies (f1 and f2) are the same as those associated in the literature(Cherry et al., 1984; Kiya and Sasaki, 1985) with the recirculation bubble (the third frequency $f_1H/U_\infty = 0.23$ is simply likely to be a harmonic of $f_2H/U_\infty = 0.12$). The lowest frequency $f_1H/U_\infty = 0.06$ can be seen to correspond to the flapping frequency which is associated with the growth and shrinkage of the bubble (Fouras and Soria, 1995). In fact, if this frequency is renormalized with the recirculation length, we find a dimensionless frequency which matches results in the literature (Cherry et al., 1984; Kiya and Sasaki, 1985).

Results show cooling the wall decreases the dominant frequencies and on the other hand heating the wall increase the frequencies as shown in Figures .

Table 2. Dominant frequencies for various wall.

Test case	f_1	f_2	f_3	f_4
Cooled	0.02	0.05	0.4	.8
Adiabatic	0.06	0.12	0.23	1.1
Heated	0.17	0.56	1.1	1.4

Table 2 summarizes the frequencies.

Figures 5 show the dynamic load, P_w/P_∞ at the wall for three different wall condition. As the wall is cooled the dynamic load on the wall is increased. The skin friction value is increased by heating the wall and decreased as the wall is cooled (Figure 6).

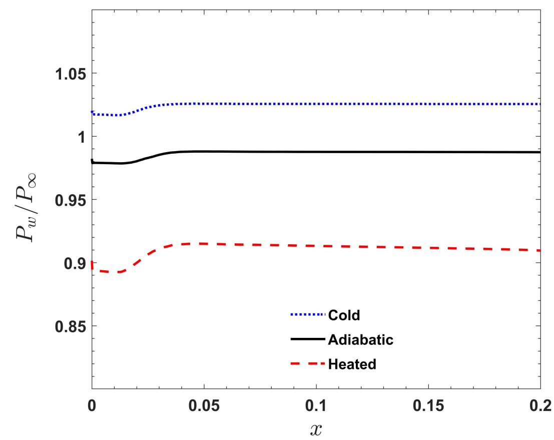

Figure 5. Dynamic load.

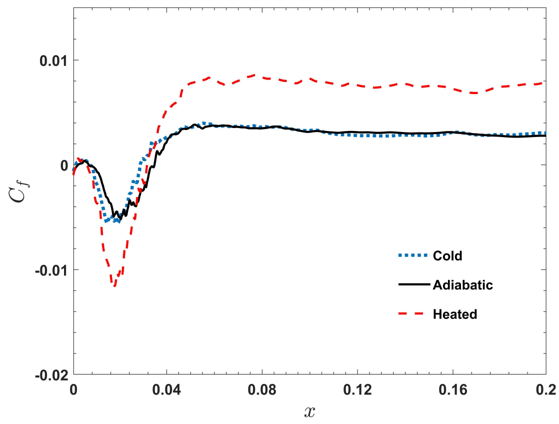

Figure 6. Skin friction

Figures 7-9 show Q-criterion contoured by the modes 1-3, respectively. The first mode (frequency) is not active in the cooled wall case, the flapping frequency becomes intense as the wall is heated. The second mode (shedding frequency) extends on the wall for the heated wall. The third mode (K-H instability) is not affected significantly by the wall thermal condition.

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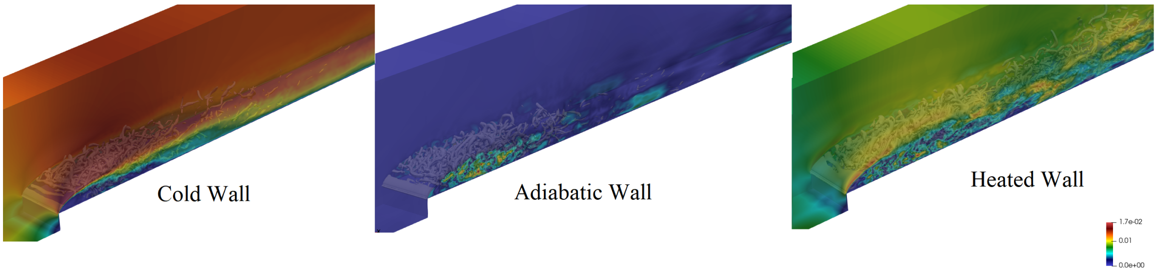

Figure 7. Mode-1

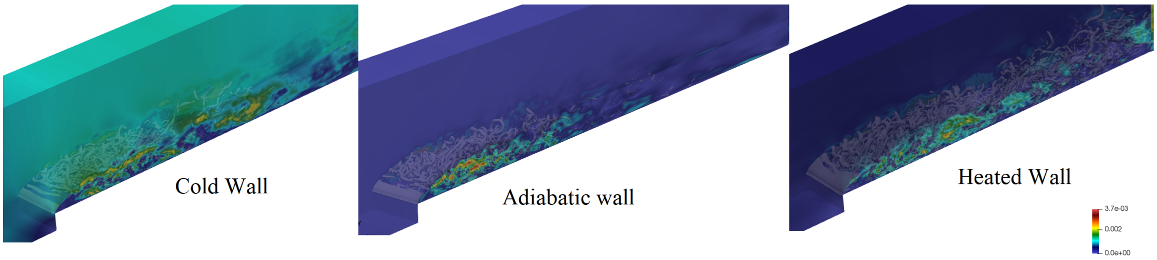

Figure 8. Mode-2

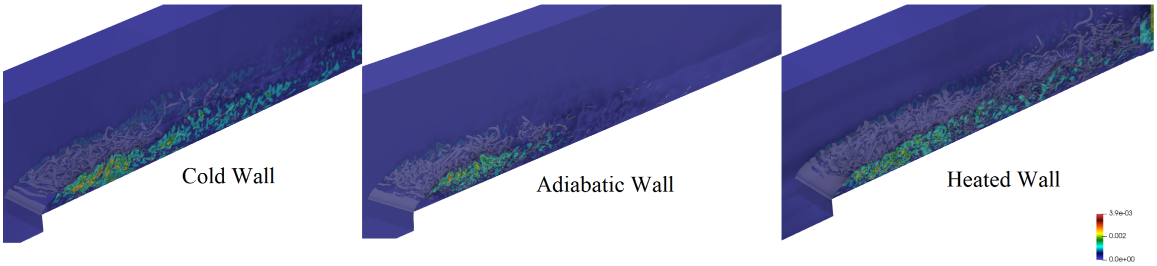

Figure 9. Mode-3

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