Flow Interaction of Shedding Vortex with Injected Normal Blowing

Khin Oo Mon* · Changjin Lee*† · Heeseok Koo**

ABSTRACT

This paper is concerned with turbulent flow computations using Large Eddy Simulation (LES) and the flow interaction of vortex shedding in a cylindrical duct flow driven by mass blowing through the wall. The purpose is to analyze non-linear combustion characteristics in the presence of vortex shedding generated in a hybrid rocket motor. Experimental studies have shown sudden changes in pressure (referred as a DC-shift), which depend on the strength of vortex strength of incoming flow. The combustion instability because of a sudden change in pressure fluctuations is mainly related with the interaction between vortex shedding. Therefore LES computation on a duct with injected normal blowing was performed to simulate the turbulent flow interactions with the behaviors of vortices and vortex structures along the injected wall.

Key Words: Large-Eddy Simulation (LES), Vortex Shedding, Hybrid Rocket, Injected Normal Blowing

1. Introduction

The presence of vortex shedding is associated with non-linear combustion characteristics in hybrid rocket. It is believed that occurance of this phenomenon is produced through the interaction of main oxidizer flow with the wall blowing generated at the surface of fuel during the regression process. Interaction between vortex shedding can cause combustion instabilities with frequency.

Even though a wide range of effort has been devoted to the understanding of the flow physics in the hybrid rocket motor in the past, significant improvement of regression rate is like to be made only after gaining a better understanding of the flow instability associated with a mixing process between a main oxidizer flow and evaporated stream from the surface.

A sudden increase in pressure during combustion, sometimes called as DC-shift, is one of the typical non-linear phenomena frequently observed in solid propellant combustion. And the term of "DC-shift" refers to the sudden rise of measured voltage corresponding to chamber pressure. The interesting feature of DC shift in solid propellant combustion is that this can be triggered only when the combustion was

---

* 건국대학교 항공우주공학과
** 서울대학교
연락저자, E-mail: cjlee@konkuk.ac.kr

pulsed appropriately. Even though the triggering mechanism for DC-shift is not completely understood so far, experimental data showed that DC shift tends to occur when the propellant burning rate increase in the presence of internal gas oscillations parallel to propellant surface. Many researchers have been done to identify the main source of DC-shift during the combustion [1-9].

Camicino et al. [7-9] performed combustion tests with two different injector configurations; axial and radial type. Their results show the characteristics of combustion stability were strongly dependent upon the injector configuration. It was found that the radial injector induced vortex shedding in the pre-chamber and generated the periodic unsteady heat release. Even with their findings that the interaction of periodic unsteady heat release with acoustic oscillations by vortex shedding is the triggering mechanism of DC shift, further research is still needed to explain why negative DC-shift are observed in the test with certain flow conditions in terms of vortex shedding and oscillatory flow near the surface.

LES studies by Lee and Na [10 and 11] were conducted for a transpired channel to investigate the effect of wall blowing on the modification of turbulence structure without accounting for chemical reactions. As seen in the case of solid rocket combustion, their results showed a flow oscillation with a specific dominant frequency near the surface. This flow oscillation was attributed to the result of the interaction between an oxidizer stream and an evaporating fuel flow from the surface. This oscillation is quite analogous to the flow pattern observed in a long solid rocket motor, known as parietal vortex shedding. The works of Na and Lee [10 and 11] and Kim et al. [11] showed that flow instability developed in the mixing layer resulted in a particular time scale. The role of intrinsic oscillatory flow, however, is not clearly understood yet.

This study focuses on the occurrence of flow interaction between vortex shedding which is related with the flow instability and evolution of the DC-shift in hybrid rocket combustion. In the present work, large-eddy simulations of compressible turbulent flow was performed with 3D cylindrical duct with normal injection. By idealizing the model as a 3D duct, it is expected to clarify the realistic flow patterns and physics in hybrid rocket combustion.

2. Numerical Simulations of a Cylindrical Duct Flow with Wall Blowing

LES analysis for a channel flow [10] and a cylindrical duct flow [11] were performed with wall blowing. In the present study, the same duct configuration is used with a denser grid system. The grids are set 192 x 64 x 128 in axial, radial and azimuthal directions respectively. A schematic of 3D computational domain of duct flow is described in figure 1.

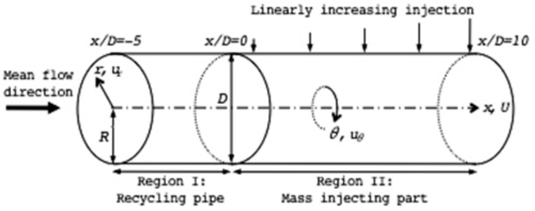

Fig. 1 Computational Domain for A Cylindrical Duct

The pipe consists of two regions: recycled part ($-5 < x/D < 0$) and wall injecting part ($0 < x/D < 10$) where D is the diameter of the pipe. In the normal injection part, the regression process is approximated by an artificial injection of the fluid through the motor surface to provide the realistic turbulence flow. No-slip, isothermal wall boundary condition is applied for all wall boundaries except for vertical mass injection walls. The numerical details for the analysis is similar to previous work [10 and 11]. Reynolds number for the calculations is set to 30,600.

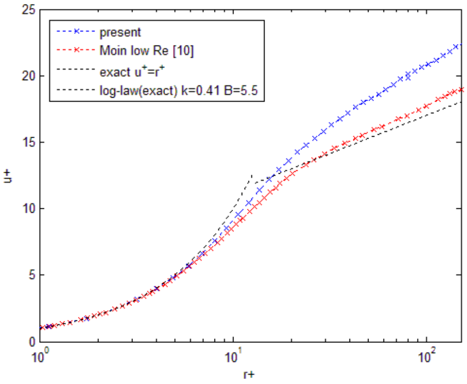

Fig. 2 Mean Velocity Profile for the Region I of Recycling Part

The verification of a developed LES code was done in figure 2 by the comparison of mean velocity with DNS analysis of Moin and Kim [12]. Even there is the disparity in Reynolds number, the log-law plot of streamwise velocity in present study yields good agreement with the compariosn of DNS and theoretical profile with k=0.41 and B=5.5 [13].

Figure 3 shows the evolution of the instantaneous axial velocity profiles at different axial locations. The selected locations are as x/D=1.65, 4.05, 6.45, 8.75, 11.2, 13.75. Since the wall blowing begins at x=5.0, the instantaneous velocity increases in the downstream of x=5.0 due to the mass accumulation. Contours of instantaneous streamwise velocity near the wall clearly show that flow structure has been altered by the application of wall injection.

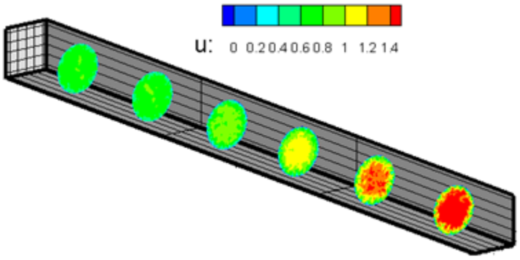

Fig. 3 The Evolution of the Instantaneous Axial Velocity Profiles at Different Axial Locations by LES

It is clearly found that velocity profiles with wall blowing have two distinct layers; a core region with higher momentum and the wall layer with lower momentum. The interaction of axial flow with wall blowing is confined only in this wall layer. Thus, diffusion flames may be formed near the edge of this layer.

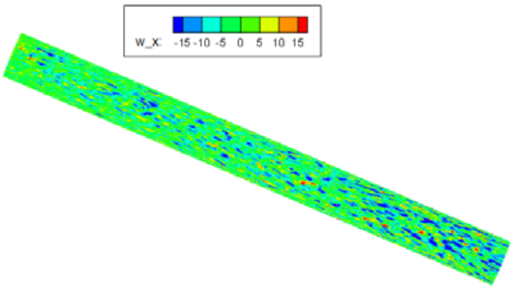

Fig. 4 The Streamwise Vortex (w_x) on the Surface of Wall Injection Part

Figure 4 shows that how turbulent structures are modified by the interaction with wall blowing. The abrupt change of flow characteristics is accompanied by the rapid movement of coherent structures away from the wall. The blowing velocity raises the turbulent structures away from the wall. So, the coherent vortices broke blowing momentum into pieces easily.

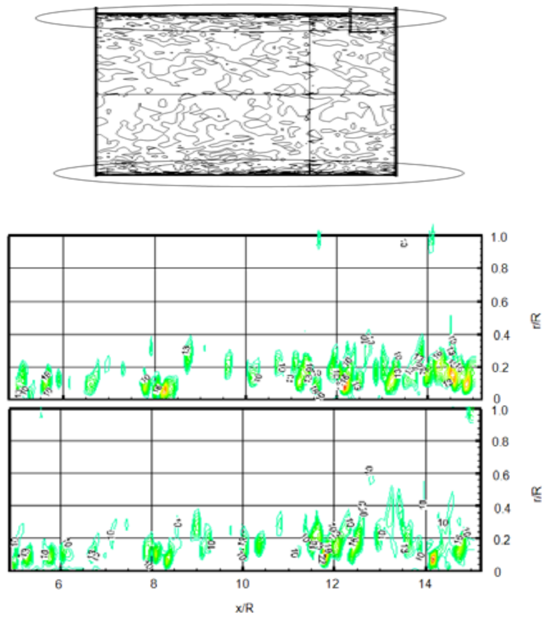

Fig. 5 Azimuthal Voriticity (w_θ) Fields at Different Time in the Region of Wall Blowing Part

The azimuthal vorticity is occurred very near the surface as shown in figure 5(a). Figure 5(b) describes the development of azimuthal vorticity profile in the axial direction generated by the interaction with wall blowing at different time. Azimuthal vorticity is defined as following equation and evaluated by taking absolute value of the curl of velocity vector;

$$|\omega_\theta| = \sqrt{\left(\frac{\partial u_r}{\partial x} - \frac{\partial u_x}{\partial r}\right)}$$

Vortex shedding is clearly found in the downstream of flow interaction of turbulent axial flow with wall blowing. And the passage of vortex shedding is responsible to the evolution of oscillatory flow near the surface region, where velocity fluctuates from negative and positive. Note that the most of vortices are confined in very thin region near the surface below r/R<0.02. Also, even though the domain of influence of vorticity in the flow gradually expands toward the center of a duct in the downstream, vortex centers remain within this very thin layer.

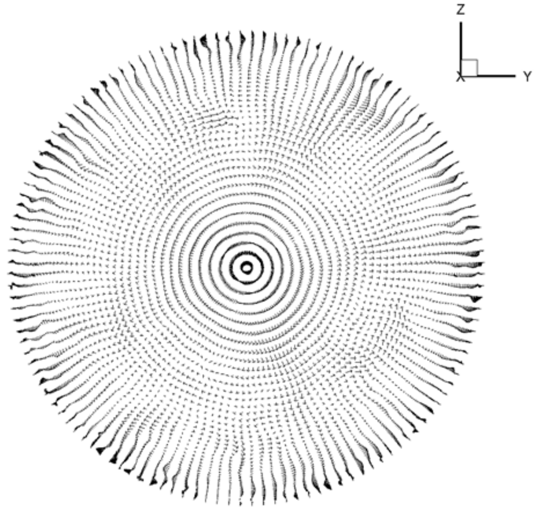

Fig. 6 Instantaneous Velocity Vectors on A Streamwise Plane of Cylindrical Duct

In figure 6, the streamwise instantaneous velocity vectors are described. The velocity fluctuations in the near-wall region are high and approaches to the center. Eddy type structures are observed in the near wall regions

3. Conclusion

Current study with LES methodology provides the interesting features of flow behavior near the wall surface. Vortex shedding with a specific frequency occurs due to the presence of shear layer which is formed by interaction of main oxidizer flow with wall blowing in the hybrid rocket combustion. Due to the interaction between mean flow and injecting flow, hydrodynamic instabilities could be developed in the hybrid rocket. Motivated by the fact concerning with the flow interaction in hybrid rocket combustion, a compressible LES study was performed for a cylindrical duct flow to find the behavior of vortex shedding.

Reference

1. Malhotra, S. and Flandro, G. A., "On the origin of the DC shift," AIAA 1997-3249, 1997
2. Flandro, G.A., Majdalani, J., Fischbach, S.R., French, J.C., "Nonlinear Rocket Motor Stability Prediction: Limit Amplitude, Triggering and Mean Pressure Shift," AIAA-2004-4054, 2004
3. Avres, J. P. and Jones, H. S., "Explanation of DC-shift in Hybrid Rocket Motor," AIAA 1997-2938, 1997
4. Avres, J. P. and Jones, H. S., "Elimination of DC-shift in Hybrid Motors," AIAA 1997-2939, 1997
5. Dijkstra F., "Ultrasonic regression rate measurement in solid fuel ramjets," AIAA 1990-1963, 1990
6. Boardmann T. A., Carpenter, R. L. and Clafin, S. E., "A Comparative Study of the Effect of Liquid versus Gaseous Oxygen Injection on Combustion Stability in 11 inch Diameter Hybrid Motors," AIAA 1997-2936, 1997
7. Carmicino, C., Russo Sorge, A., "Performance Comparison between Two Different Injector Configurations in a Hybrid Rocket," Aerospace Science and Technology 11, 2007, pp 61-67
8. Carmicino, C., Russo Sorge, A., "On the Role of Vortex shedding in Hybrid Rockets Combustion Instability," AIAA 2008-5016, 2008
9. Carmicino, C., "Acoustics, Vortex Shedding, and Low-Frequency Dynamics Interaction in an Unstable Hybrid Rocket," J. Propulsion and Power Vol. 25, No. 6, 2009
10. Na, Y. and Lee, C., "Intrinsic Flow Oscillation in Channel Flow with Wall Blowing," 44th AIAA/ASME/SAE/ASEE, Joint Propulsion Conference & Exhibit, Hartford, CT. AIAA 2008-5019, 2008
11. Kim, B., Na. Y. and Lee, C., "Non-linear Combustion and LES Analysis with Wall Blowing in Hybrid Rocket," 46th AIAA/ASME/SAE/ASEE, Joint Propulsion Conference & Exhibit, Nashville, Tennessee, 2010
12. John Kim, Parviz Moin and Robert Moser., "Turbulence Statistics in Fully Developed Channel Flow at Low Reynolds Number," J. Fluid Mech. 1987, vol. 177, pp. 133-166
13. P. A. Durbin, B. A. Petterson Reif., "Statistical Theory and Modeling for Turbulent Flows," First Ed, John Wiley & Sons, Ltd, England, pp. 62-65, 2001