LARGE-EDDY SIMULATION OF CHANNEL GAS-PARTICLE FLOW INDUCED BY WALL INJECTION WITH FORCED PRESSURE OSCILLATIONS

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Abstract A numerical analysis of the internal flow is performed to improve the current understanding and modelling capabilities of the complex flow characteristics encountered in combustion chambers of solid rocket motors (SRMs) in presence of forced pressure oscillations. The two-phase flow is simulated with a combined Eulerian–Lagrangian approach using large-eddy simulation. The filtered Navier–Stokes equations are solved numerically for the gas phase. The particulate phase is simulated through a Lagrangian deterministic and stochastic tracking models to provide particle trajectories and volume fraction of particulate phase. The results obtained highlight the crucial significance of the particle dispersion in turbulent flow and high potential of statistical methods. Strong coupling between acoustic oscillations, vortical motion, turbulent fluctuations and particle dynamics is observed.

INTRODUCTION

Aluminium particles in solid propellant serve two purposes: increasing specific impulse and suppressing combustion instability (damping effect). Unlike the other ingredients, aluminium particles burn in a significant portion of the chamber of solid rocket motor (SRM) and produce alumina smoke and agglomerates that are carried out into the flow field [1]. Aluminium particles affect combustion instabilities by acting as driving or damping mechanisms [2]. The two-phase flow with distributed combustion of particles and forced oscillations significantly influences SRM performance in terms of acoustic instability, slag accumulation, nozzle erosion and two-phase losses [3]. A reliable stability prediction includes the numerical simulation of the turbulent reactive two-phase flow in the combustion chamber of SRM (Figure 1).

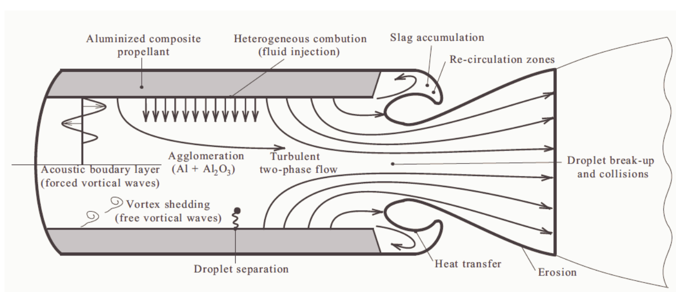

Figure 1. Combustion chamber.

SRMs are subject to pressure oscillations caused by vortex shedding and acoustic feedback resulting from impingement of the vortices on the nozzle and other obstacles [4]. The oscillatory flow field in a SRM consists of three distinct types of wave motions: acoustic (irrotational and compressible), vortical (rotational and incompressible) and entropy (arising from unsteady heat release) modes [5, 6]. The coupling between the acoustic wave and the incoming radial mass flow from the propellant surface generates fluctuating vorticity and causes the energy transfer from the acoustic to the vortical field (flow-turning energy losses). The interactions between entropy fluctuations and non-uniform flow act as a strong source term for driving acoustic oscillations in regions with large velocity gradients. The three waves, along with the transient combustion response of propellant, dictate the stability behavior of SRMs. Aluminium droplet combustion and alumina residue behavior in the chamber affect combustion instabilities by acting as driving or damping mechanisms [2].

A numerical analysis of the internal flow is performed to improve the current understanding and modelling capabilities of the complex flow characteristics encountered in combustion chambers of SRMs in presence of forced oscillations and combustion of particles. In order to extend the reliability of numerical calculations as a predicting tool to be used for industrial applications in design and development of SRMs, one needs to improve the level of accuracy of physical models and the effectiveness of numerical schemes. The study is intended to develop numerical analysis of the internal two-phase flows with emphasis on the momentum and energy transfer between the gas and solid particles in presence of forced oscillations and combustion of particles. To meet the aim of the study the specific objectives are addressed: (i) to study particle dynamics in the turbulent flow field and combustion of particles; (ii) to examine the interactions between turbulent and forced oscillatory flow fields; (iii) to explore the effects of particles on steady and unsteady flow motions.

The two-phase flow is simulated with a combined Eulerian–Lagrangian approach. The filtered Navier–Stokes equations are solved numerically for the gas phase. The particulate phase is simulated through a Lagrangian deterministic or stochastic tracking models to provide particle trajectories [7, 8].

MODEL AND NUMERICAL METHOD

Flow solution is provided using cell-centered finite volume formulation of the unsteady 3D compressible Navier–Stokes equations on structured mesh. Governing equations are solved by the 5th step Runge–Kutta time marching scheme. Piecewise parabolic method (PPM) and Chakravarthy–Osher scheme are applied to inviscid fluxes, and central difference scheme of the 2nd order is applied to viscous fluxes. The feature of the flow induced by wall injection is that the gas velocity in the bulk of the computational domain is much smaller than the acoustic speed. The conventional numerical algorithms developed for compressible flows encounter disparity of the eigenvalues of the system and singular behaviour of the pressure gradient in the momentum equation. Preconditioning block-Jacobi technique in conjunction with implicit dual time-stepping integration method is employed to stabilize numerical calculations and speed up convergence. The scheme is efficient and robust over a wide range of Mach numbers. The numerical method is stable and allows the selection of the integration time step to be dictated by physical processes rather than numerical stability.

RESULTS AND DISCUSSION

The unsteady calculations are performed in the following manner. After convergence toward a steady state solution, the channel flow is excited close to its first longitudinal mode by means of one period of head-end forcing. Pressure oscillations equal to 5% of the head-end mean pressure at imposed acoustic frequencies are forced at the head-end in order to analyse unsteady flow field. Then the response of the flow field to that perturbation is analysed in term of frequency and exponential damping. The numerical model is applied to simulate internal gas-particle flow focusing on the influence of the turbulence effects on the flow structure, particle trajectories and dispersion, and impact of particles on vertical and acoustic flow fields. Computations of the two-phase flow are performed in non-coupled manner and fully coupled manner.

Acoustic oscillations exert a strong influence on unsteady flow evolution. In particular, single-harmonic oscillations excite a fluctuating flow with a broadband frequency spectrum (this phenomenon is referred to as acoustically induced turbulent motion). Generation of turbulence by organized external forcing is viewed as an energy transfer process from the acoustic flow field to the turbulent flow field. The coupling between the Reynolds stresses and the gradient of acoustic velocity provides a mechanism to transfer the kinetic energy from acoustic motions to turbulent fluctuations. Furthermore, an early transition from laminar regime to turbulent one occurs depending on the forcing amplitude and frequency. The effect of energy exchange tends to be more profound for low-frequency acoustic oscillations.

Particles are inclined to damp and to disperse the waves by slowing them. The damping is more pronounced when the particle response time is close to the acoustic time period (the acoustic Stokes number is close to unity). The damping increases with the particles loading. There exists the optimum particle size at which the maximum damping of acoustic motion occurs. For small particles than closely follow the wave motions, the relative velocity and temperature differences between two phases become so small that the viscous and thermal dissipation is insignificant. The large particles hardly follow the wave motions to cause effective momentum and energy exchange, thereby leading to negligible acoustic attenuation. Propagation of acoustic waves in gas-particle mixture involves a series of rarefaction and compression processes, during which both momentum and thermal relaxation take place between particles and gas. For small particles, equilibrium is reached, and particles are treated as additional gas species. For large particles, the gas remains almost unchanged, and the acoustic wave speed has a value corresponding to that in a gas.

Particle trajectories are computed for different particle diameters. A significant difference exists between particle trajectories calculated from laminar and turbulent flow fields. Small particles deviate from their mean flow paths under the influence of gas flow oscillations and turbulent dispersion, and enhance interphase interactions. The dispersion of particles is controlled by the particle Stokes number. Limiting trajectory of particles where concentration of particles increases is clearly observed in the calculations. Dispersion of particles leads to increasing the particles residence time in the channel and their combustion rate. The particle damping effect is defined by the particle loading and the ratio of particle relaxation time to turbulent time scale. The particles lead to damping of turbulent fluctuations and have laminarization effect resulting in additional dissipation of turbulent kinetic energy due to relative motion of gas and particles. The turbulence modulation effect is more visible for small particles.

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