CHAPTER – 5

NUMERICAL RESULTS & DISCUSSIONS

5.1 INTRODUCTION

This section describes the results obtained using numerical methodology for the Ignition Overpressure simulation during the start-up of solid rocket motors. Governing equations, boundary conditions, turbulence model and convergence criteria have been already covered in the earlier chapter. Numerical simulations have been carried out for full size motor and small size motor without nozzle shutter using the CFD software tool FLUENT. The Spalart–Allmaras turbulence model has been adopted in the turbulent compressible flow simulation. The steady state mass flow rate of the full size motor is 1950 kg/s. The exhaust flow from the motor has been simulated for three different stand-off distances 3De, 4.5De and 6De, where De is the nozzle exit diameter and three ignition times of 50 ms, 100 ms and 150 ms. The computational domain with boundary conditions for the full size motor is shown in Figure 3.4. The entire domain is discretized into 2 lakhs structured cells of uniform size. Numerical solution is obtained by advancing with respect to time, in steps of 0.5 millisecond time increments.

The steady state mass flow rate of the small size motor is 13 kg/s. The exhaust flow from the small size motor has been simulated for the ignition time of 50 ms. The computational domain for the small size motor is shown in Figure 3.5. The entire domain is discretized into 1 lakh structured cells of uniform size. Numerical solution is obtained by advancing with respect to time, in steps of 0.5 millisecond time increments.

5.2 NUMERICAL RESULTS AND DISCUSSIONS

5.2.1 FULL SIZE MOTOR

FLUENT simulations have been carried out for a full scale motor using the Spalart-Allmaras turbulence model. This motor could deliver a steady state mass flow rate of 1.95 tonnes/s propellant and has a nozzle area ratio of 12.1. The length of the combustion chamber is 15.5 m. To visualize and understand the propagation of the blast wave phenomenon, nine different cases have been simulated by keeping a flat
plate at a distance of 3De, 4.5De and 6De below the nozzle exit as shown in the earlier Chapter (Figure 3.5), where De is the nozzle exit diameter. It is to be noted here that a flat plate has been considered for numerical simulation, instead of a jet deflector in a classical launch vehicle lift-off case. An assumed linear mass flow rate variation with time for exhaust gas has been prescribed as input at the combustion chamber. Figure 5.1 shows the linear mass flow rate variation of propellant for three ignition times of 50 ms, 100ms and 150 ms. The resultant chamber pressure rise for these three ignition times in the combustion chamber is shown in Figure 5.2. The field pressure has been monitored at four locations 1, 2, 3 & 4 as shown in Chapter 3. The results predicted for the full size motor are presented in Figures 5.3 to 5.16. For the sake of comparison, predictions carried out for small size motor are also presented in Figures 5.17 and 5.20.

The simulation begins with stagnant air filled inside the combustion chamber, nozzle and surroundings of the vehicle at time \( t = 0 \). For time \( t > 0 \), the combustion chamber pressure continues to increase due to hot gas inflow until it reaches steady state value. The hot gaseous products first occupy the combustion chamber volume and they push out the stagnant air inside the combustion chamber. This transient pushing action generates a blast wave which spreads spherically outside the nozzle as shown in Figure 5.3. This figure clearly illustrates that the most of the energy of the blast wave is radiated in the downstream direction of the nozzle. The blast wave decays as it propagates. Figure 5.4 shows the temperature contours of the exhaust flow from the nozzle. From a comparison of the pressure contours and temperature contours of Figure 5.3 & Figure 5.4, it is clearly understood that Ignition Overpressure wave is followed by the gaseous flow. Ignition Overpressure wave emerges out of the nozzle much before the flow, i.e. much before the nozzle is in fully flowing condition. The blast wave has a frequency of 20Hz approximately. This low frequency overpressure wave would travel more distance and even damage sensitive electronic components inside the heat shield area.

Figure 5.5 shows the amplitude of IOP at a stand-off distance of 3De and for three ignition times, 50 ms, 100 ms and 150 ms at four locations near the vehicle and near the base plate. The first peak in all the plots represents the magnitude of IOP and it is followed by reflections from the wall and the vehicle. From each plot it is seen that with decrease in ignition time, the amplitude of the IOP increases. The same trend
is being followed for the stand-off distances of 4.5De and 6De as shown in Figures 5.6 and 5.7.

Figure 5.8 depicts the variation of overpressure amplitude for the ignition time of 50 ms and for three stand-off distances 3De, 4.5De, 6De. From this figure, it is seen that for “location 1” and “location 2”, the magnitude of IOP observed is higher with an increase in stand-off distance. It may be because of the source of IOP moving nearer to the monitoring locations 1 and 2. At location 3 for standoff distance 6De, the magnitude of IOP observed is more compared to that of the stand-off distance of 3De. This trend may be attributed to the merging of shock waves during outward propagation. At location 4 also, it is observed that the overpressure amplitude is more for 3De compared to that for 6De. The same trend is observed for the other ignition times also, as shown in Figures 5.9 and 5.10.

Figures 5.11(a) and (b) show the axial downstream directivity of the blast wave at 60° and 90° to the nozzle axis, respectively. From this, it is clear that the blast wave decays with time and distance, as it propagates. Figures 5.12(a) & (b) show the angular directivity of the blast wave at 5 m radius and 10 m radius from the nozzle exit respectively. The blast wave amplitude decreases when the angle from the nozzle axis increases.

Figures 5.13(a) and 5.13(b) show the overpressure amplitude and its corresponding frequency at 30° and 1.5De radius from the nozzle exit, respectively. The FFT analysis of the wave shows a dominant peak at a frequency range 0-10 Hz. Figures 5.14(a), 5.15(a) and 5.16(a) show the overpressure amplitude at different locations and their corresponding FFT are shown in Figures 5.14(b), 5.15(b) and 5.16(b) respectively. From these figures, it can be concluded that the wave shows a dominant peak at a frequency range of 0-10 Hz. Similar trend has also been observed by Dougherty et al. (1982) for STS-1, which shows a wave form corresponding to a dominant frequency of just less than 10Hz.

5.2.2 SMALL SIZE MOTOR

FLUENT simulations have been carried out for small size motor using the Spalart-Allmaras (S-A) turbulence model. This motor has a steady state mass flow rate of 13 Kg/s propellant and has a nozzle area ratio of 12.1. The length of the
combustion chamber is 1.17 m. The motor has been positioned horizontally and supersonic jet is directed to atmosphere.

Figures 5.17(a) and 5.17(b) show the variation of overpressure wave amplitude and FFT analysis at 30° and 1.5De from the nozzle exit respectively. Figure 5.17(a) shows the decay of the overpressure amplitude with respect to time. It should be noted that since, no jet deflector plate has been provided below the nozzle exit, there are no reflections from the downstream boundary. The FFT analysis of the pressure fluctuation shows a dominant peak at a frequency range of 100 – 200 Hz. From this it can be concluded that the small motors can be characterized by high frequency fluctuations as compared to full size motors which show a low frequency blast wave as discussed above. Similar trends were observed by Lai and Laspesa (1982) with their experiments on full size and small size motors. Figures 5.17(a), 5.18(a), 5.19(a) and 5.20(a) show the variation of overpressure wave at different locations and their corresponding frequencies are shown in Figures 5.17(b), 5.18(b), 5.19(b) and 5.20(b) respectively.

![Fig 5.1 Propellant mass flow rate variation](image1)

![Fig 5.2 Chamber pressure variations](image2)
Fig 5.3 (a) Pressure (Pa) Contour  
5.4(a) Temperature (°K) countours
Fig 5.3(b) Pressure (Pa) Contour

Fig 5.4(b) Temperature (°K) Contours
Fig. 5.5 Overpressure amplitude at locations 1, 2, 3 & 4 for stand-off distance = 3De

Fig. 5.6 Overpressure amplitude at locations 1, 2, 3 & 4 for stand-off distance = 4.5De
Fig. 5.7 Overpressure amplitude at locations 1, 2, 3 & 4 for stand-off distance = 6De

Fig. 5.8 Overpressure amplitude at locations 1, 2, 3 & 4 for ignition time = 50ms
Fig. 5.9 Overpressure amplitude at locations 1, 2, 3 & 4 for ignition time = 100ms

Fig. 5.10 Overpressure amplitude at locations 1, 2, 3 & 4 for Ignition time = 150ms
Fig. 5.11 (a) Axial downstream directivity of the overpressure wave at 60° to the nozzle axis

Fig. 5.11 (b) Axial downstream directivity of the overpressure amplitude at 90° to the nozzle axis

Fig. 5.12 (a) Angular directivity of the overpressure wave at 5 m radius from nozzle exit

Fig. 5.12 (b) Angular directivity of the overpressure wave at 10 m radius from nozzle exit

Fig. 5.13 (a) Overpressure wave at 30° and 1.5D, radius from the nozzle exit.

Fig. 5.13 (b) FFT of Overpressure wave at 30° and 1.5D.

Fig. 5.14 (a) Overpressure wave at 60° and 1.5D, radius from the nozzle exit.

Fig. 5.14 (b) FFT of Overpressure wave at 60° and 1.5D, radius from the nozzle exit.
Fig. 5.15 (a) Overpressure wave at 30° and 3Dₐ radius from the nozzle exit.

Fig. 5.15 (b) FFT of Overpressure wave at 30° and 3Dₐ radius from the nozzle exit.

Fig. 5.16 (a) Overpressure wave at 60° and 2Dₐ radius from the nozzle exit.

Fig. 5.16 (b) FFT of Overpressure wave at 60° and 2Dₐ radius from the nozzle exit.

Fig. 5.17 (a) Overpressure wave at 30° and 1.5Dₐ radius from the nozzle exit of small size motor.

Fig. 5.17 (b) FFT of Overpressure wave at 30° and 1.5Dₐ radius from the nozzle exit of small size motor.

Fig. 5.18 (a) Overpressure wave at 60° and 1.5Dₐ radius from the nozzle exit of small size motor.

Fig. 5.18 (b) FFT of Overpressure wave at 60° and 1.5Dₐ radius from the nozzle exit of small size motor.
Fig. 5.19(a) Overpressure wave at 30° and 3D_e radius from the nozzle exit of small size motor.

Fig. 5.19(b) FFT of Overpressure wave at 30° and 3D_e radius from the nozzle exit of small size motor.

Fig. 5.20(a) Overpressure wave at 60° and 3D_e radius from the nozzle exit of small size motor.

Fig. 5.20(b) FFT of Overpressure wave at 60° and 3D_e radius from the nozzle exit of small size motor.