Comparisons between Fast Shock Tube Simulations and Tests

V Mehra¹, V Mishra, Sijoy CD and S Chaturvedi
Computational Analysis Division
Bhabha Atomic Research Centre
IDA 'B' Block, 4th cross-road, Autonagar, Visakhapatnam 530 012, A.P., India

E-mail: vmehra10@yahoo.com

Abstract. The experiments of Menikoff et al on a projectile hypervelocity launcher using a fast shock tube (FST) are modelled using smooth particle hydrodynamics (SPH) technique. In a FST, the progressive detonation of a co-axial HE cylinder induces a cumulative shock in the liquid-filled core. This shock hits a thin flyer and accelerates it to hypervelocity. The comparisons are made on flyer velocity profile, peak pressure and shock speed in liquid core. The SPH reproduces the qualitative and quantitative aspects of the FST and is well-suited to the high strain-rate feature of this experiment.

1. Introduction
The design of hypervelocity launch systems requires understanding physics of projectile acceleration at high driving pressures (megabar range) and short acceleration times (few μs). The Fast Shock Tube (FST) has been proposed as a hypervelocity launcher [1] and as an injector for an electromagnetic rail gun [2]. The FST consists of a cylinder of high-explosive (HE) that drives a flat, axial shock in a fluid-filled core inside the HE. First experiments on FST were carried out by Menikoff et al [1]

Drive conditions much higher than direct HE drive can be obtained in FST. The core contains propellant material such as polystyrene foam or hexane. The HE is initiated at the left hand of the FST assembly in a cylindrically symmetric way and the detonation wave acts like a virtual piston that drives a strong axial wave in the core. The shocked core hits the flyer and accelerates it to a very high velocity. The choice of the design parameters is vital and these include the diameters and lengths of HE tube and core, type of HE and core density. The proper choice of these parameters achieves the flat shock and uniform flow conditions behind the shock in the core [2]. The experimental parameters are so set that the axial shock velocity in the core equals the detonation velocity of the HE otherwise the axial shock would overtake the detonation front and send a precursor wave into the HE leading to a loss in the core shock intensity.

2. The FST tests
The schematic of FST experiments that were carried out by Menikoff et al is shown in fig.1. The core of the shock tube is 6.746 cm long by 0.856 cm inner diameter and is surrounded by a HE cylinder of diameter 5 cm. The HE chosen is PBX-9501 that has a Chapman-Jouget (CJ) detonation velocity of 8.8 km/s and a CJ pressure of 370 kbar. The working fluid in the inner tube is n-hexane with density

¹ To whom correspondence should be addressed.
0.657 g/cm³. The parameters were chosen so that the test is close to the energy limit for propagating an axial shock---with a lower working fluid density or higher HE energy, the axial shock would get ahead of the detonation front and send a precursor back into the HE and thus complicating the analysis and weakening the axial shock that propagates in the hexane tube [1].

A mild steel (MS) flyer plate of 0.79 mm thickness is placed at the end of hexane tube, followed by a 1.5 cm air gap that separates it from a lucite block. The axial shock in the hexane sends a shock into the flyer plate. The shock arriving at the rear free surface changes the surface roughness and thus the surface reflectance is also changed. The rear flyer surface is illuminated with a flash lamp. The arrival of the shock at the free surface is thus marked with the change in intensity of the reflected light. Then the air gap between the flyer rear surface and the lucite block is compressed and heated to white-hot by the motion of the flyer plate and the impact of the flyer on the lucite is marked by a bright flash. The flyer plate velocity is measured by the time delay between the reflectance change and the flash. The shock strength in the hexane is obtained by impedance matching [1]. The arrival times of the shock at flyer surface and the flyer impact at the lucite are radially resolved. The radial profile of the flyer plate velocity is obtained from the radially resolved flyer plate timings.

3. The Simulations

The FST experiments of Menikoff et al are modelled using the Smooth particle hydrodynamics (SPH), a meshless technique often used to model high-deformation events such as hypervelocity impact and penetration, jet formation in shaped charges detonation etc. [3]. The SPH equations are obtained from the continuum equations by discretization onto a set of co-moving nodes. The fields of continuum mechanics---pressure, density, temperature stress and strain tensors are defined on the nodes. The node-node interaction is obtained by the discretization of continuum equations and is mediated by a kernel function W. The function W depends upon the inter-node distance and a parameter called the
smoothing length \( h \) that measures the zone of influence of a SPH node. For the specific case of cubic spline kernel function that is commonly used in SPH, the node-node interaction vanishes for inter-node distance that is greater than \( 2h \). The kernel \( W \) are normalized and reduce to delta function in the limit \( h \to 0 \) [3].

The SPH model of the experimental situation is built by filling up the geometry with SPH nodes. For FST model, we have PBX-9501 high explosive (HE), n-hexane working fluid and mild steel as the flyer and the casing material for HE and n-hexane. The nodes are initially placed on a regular lattice that may be square or triangular. The ratio of smoothing length \( h \) to average initial inter-node spacing \( d \) is an important SPH parameter relevant to the stability of the SPH algorithm. Initially the smoothing lengths are set by scaling the inter-node spacing \( d \), thus \( h/d \) is taken as a global ratio, between 1 and 2 [4]. The local resolution is adaptively varied by evolving the smoothing lengths in space and time according to the Benz prescription [5].

Simulations in this paper have been carried out in two-dimensional (x-y) Cartesian geometry. The initial placement of SPH nodes is shown in fig.2. There are three types of nodes corresponding to HE, n-hexane and mild steel flyer. The HE is modelled with Jones-Wilkins-Lee (JWL) equation of state (EOS), hexane and MS are modelled with EOS of Gruneisen type[1]. Von Mises plastic flow criterion is used for MS.

The detonation is simultaneously initiated at \( y=\pm 2.5 \) i.e. along the periphery of HE charge. The detonation produces an axial shock in the hexane core that moves along the x-axis. The nodal configurations and pressure distribution are shown in Fig.3 at 6 \( \mu \)s and 9 \( \mu \)s after HE initiation.

**Figure 3:** SPH nodal configurations (left) and pressure distribution (right) at 6 \( \mu \)s (top) and 9 \( \mu \)s (bottom) after the detonation is initiated. The axial shock velocity is determined from the visual inspection of these plots. On left, HE nodes are shown green, hexane nodes are blue and MS nodes are red. On right, red marks nodes with pressure > 200 kbar; green marks nodes with pressure >100 but <200 kbar; blue marks nodes with pressure >50 kbar but <100 kbar and pink marks pressure <50 kbar. The axis of the shock tube is along x-axis. Distances are in cm.
Shock velocity of 9.8 km/s is determined from the relative positions of the axial shock at different times. Experimentally, the shock speed is 8.9 km/s [1]. The SPH simulations yield 330 kbar as the peak pressure generated within hexane as the axial shock hits the flyer (experimentally 290 kbar). The simulations is ended at 12 μs from the HE initiation and the final nodal configuration is shown in Fig 4 below.

Figure 4: The pressure distribution and flyer deformation as the axial shock hits the flyer (shown in light blue). The red marks nodes where pressure >200 kbar, green marks nodes with pressure >100 kbar but <200 kbar. Blue marks nodes where pressure >50 kbar but <100 kbar and pink are nodes with pressure <50 kbar. Distances are in cm.

Figure 5. The axial velocity ($v_x$) profile of the flyer along the y-axis. The red line is SPH result and green is from Menikoff experiment. Experimentally, the central part of the flyer reaches 3 km/s and the outer part 2 km/s [1]. The corresponding values from our 2D simulations are 3.5 km/s and 2.5 km/s resp. Along x-axis is radial distance from core axis in cm and y-axis is axial velocity in km/s.

The fig.5 shows the comparison between the experimental velocity profile and the velocity profile produced through SPH. The peak flyer velocity from SPH is 3.5 km/s (exp. 3 km/s). The agreement is satisfactory considering the 2D nature of our simulations.

4. Conclusions

The experiments of Menikoff et al on a projectile hypervelocity launcher using a fast shock tube (FST) are modelled using smooth particle hydrodynamics (SPH) technique. In a FST, the progressive detonation of a co-axial HE cylinder induces a cumulative shock in the liquid-filled core. This shock hits a thin flyer and accelerates it to hypervelocity. The comparisons are made on flyer velocity profile, peak pressure and shock speed in liquid core. The SPH reproduces the qualitative and quantitative aspects of the FST quite well and is well-suited to the high strain-rate feature of this experiment.

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