Numerical Simulation of the effects of a muffler on shock sound mitigation

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1 Introduction

Experiments in detonation tubes are used to study the fundamental physics of explosions and high-speed combustion. These experiments have provided insights into the properties and structure of propagating detonations as well as the deflagration-to-detonation transition (DDT) which has applications in explosion safety, astrophysical combustion and detonation engines for propulsion ([2]). Nearly all of the experimental detonation facilities available for academic research are small-scale due to the challenges associated with the handling and storage of explosive materials. Among the larger scale facilities was the Gas Explosion Research Facility at Lake Lynn ([1]) which was used to carry out detonation studies on methane-air mixtures.

The upcoming Detonation Research Test Facility (DRTF) at Texas A&M University consists of the detonation tube (DT), which is currently planned to be 200 m long and 2 m in diameter. Once complete, the DRTF would be used to carry out large-scale experiments of shock interactions with high-speed turbulent flames and their role in DDT. Unlike other large-scale detonation facilities, the DRTF will be constructed close to habitation. This presents the unique challenge of developing mitigation strategies to keep the sound intensity within permissible limits. Initial experiments were performed in [6] using scaled down shocktubes to study the pressure decay in open air. Based on these experiments, a relationship was developed to show the pressure decay with distance as a function of the tube diameter. This showed that the sound levels of the DT would be higher than regulatory limits.

Since the sound intensity is directly proportional to the overpressure, we need to minimize the pressure of the gas prior to its expansion in the atmosphere. Hence, an idea was proposed that allows the high-pressure flow to expand in a large enclosed chamber, called the muffler, before being released into the atmosphere. This paper describes one step in developing a design for the muffler chamber. Here, we evaluate several design configurations for the muffler and compare their effectiveness. This is done by solving both the two-dimensional (2D) and three-dimensional (3D), unsteady, Euler equations for a scaled down model of the muffler. The resulting flow field and the ability of the configurations to reduce overpressure are discussed.

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2 Numerical setup

The computational domain represents a 1:10 scaled down model of the muffler. As per our design, $V_M = 9V_{DT}$ where V_M is the volume of the muffler and V_{DT} is the volume of the detonation tube. The governing equations (Euler equations) are solved assuming an ideal gas equation of state with $\gamma = 1.4$ and the molecular weight of the gas $M_w = 28.97$ g/mol. We solve the unsteady, compressible, Euler equations where the hydrodynamic flux terms are computed using unsplit, fourth-order, flux-corrected transport (FCT) given in [3]. The time integration is performed explicitly using a second-order Runge-Kutta scheme described in [5] with the timestep being limited by the CFL condition. The FCT algorithm is integrated with the AMReX [4] adaptive mesh refinement library for parallelization and grid refinement.

2.1 Two-dimensional setup

In 2D, the muffler is approximated as a rectangle with the high-pressure gas from the DT entering through an opening at one end. Four locations for the exit vent are tested. In each case, the domain consists of an inflow from the DT and one exit vent. Figure 1 shows a schematic of the computational domain with the location of the four exit vents. We assume a slip, adiabatic wall at all the boundaries. A zero-gradient outflow boundary condition is imposed at the exit vents. A moving normal shock at Mach number, $Ma = 3.0$ enters the domain through the inflow boundary. High-pressure gas enters into the domain for an inflow time t_{in} that is calculated based on the volume of the DT and muffler. When $t > t_{in}$, zero-gradient outflow boundary conditions are applied to the inflow as well. The inflow time $t_{in} = 5.4$ ms and the total simulation time $T = 200$ ms. Mesh refinement is performed dynamically tracking the shock and high-pressure regions, and the finest cell size is $\Delta x = 0.439$ cm.

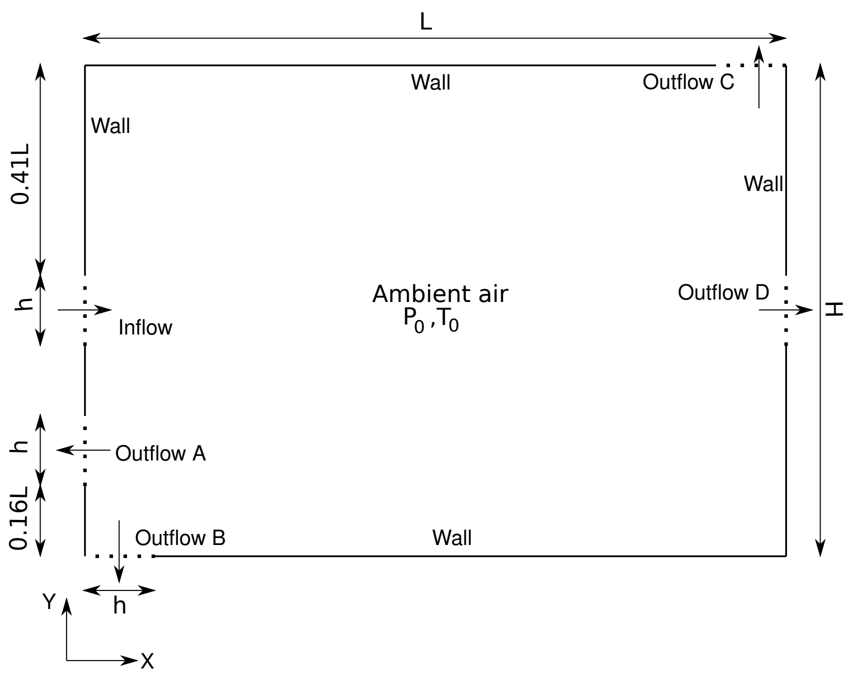


Figure 1: Computational setup of the muffler in 2D. Each configuration consists of inflow and one exit vent. $L = 900$ cm, $H = 112.5$ cm, $h = 20$ cm

2.2 Three-dimensional setup

The muffler is approximated as a rectangular box in 3D with the same length and height as the 2D case. Figure 2 shows a schematic of the 3D problem being studied. The computational domain consists only of the muffler with the detonation tube (DT) being modeled through inflow boundary conditions. We assume a slipping, adiabatic wall at all the boundaries. The inflow boundary is modeled using Chapman-Jouguet (CJ) conditions at $Ma = 3.0$ for a stoichiometric methane-air mixture. The CJ values are obtained from [7] and are $P_{CJ} = 16.89P_0$, $T_{CJ} = 9.46T_0$ where $P_0 = 1$ atm and $T_0 = 298$K. The inflow time $t_{in} = 30.47$ ms and the total simulation time is $T = 88.5$ ms.The finest cell size in the 3D calculations is $\Delta x = 0.878$cm.

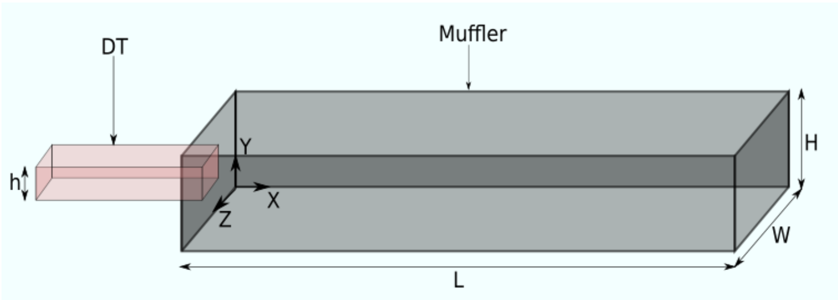


Figure 2: Computational setup of the muffler in 3D. In this work, L= 900cm, W=H= 112.5cm and h= 20cm. Computational domain consists only of the muffler. The DT is modeled as an inflow and is shown only for reference

2.3 Initial conditions and inflow time

At $t = 0$, the gas inside the muffler is in a quiescent state with $P = P_0$, $T = T_0$. The inflow time (t_{in}) is calculated by assuming that the entire DT is filled with gas at $Ma = 3.0$ with the pressure and temperature being determined by normal shock relations (for 2D) and CJ conditions(for 3D). Let $f_{in} = A_{in}u_{in}$ be the volume flow rate into the muffler where A_{in} is the inflow area and u_{in} is the inflow velocity. Then, t_{in} is given by:

$$t_{in} = \frac{V_{DT}}{f_{in}}$$

$$\text{For 2D, } V_{DT} = \frac{V_M}{9} = 1.125\text{m}^2,\ A_{in} = 0.2\text{m},\ u_{in} = Ma \times \sqrt{\gamma R T_0} = 1038\text{m/s}$$

$$\Rightarrow t_{in} = 5.4 \text{ ms}$$

$$\text{For 3D, } V_{DT} = 1.265625\text{m}^2,\ A_{in} = 0.04\text{m}^2 \ \Rightarrow t_{in} = 30.48 \text{ ms}$$

3 Results

3.1 Two-dimensional results

The 2D computations are meant to provide a qualitative picture of the flow in the muffler. The computations show that the high-pressure gas initially expands outwards until it is reflected off the top and bottom wall ($y = 0$, $y = H$). Then, it evolves into a essentially 1D shock propagating that reflects off the muffler end walls ($x = 0$, $x = L$). When $t > t_{in}$, an expansion fan forms and reflects off the back wall ($x = 0$). The maximum overpressures at each outflow vent that occur after the first reflection off the back wall are given in Table 1. We see that the exit vents C & D experience much higher overpressures than vents A & B.

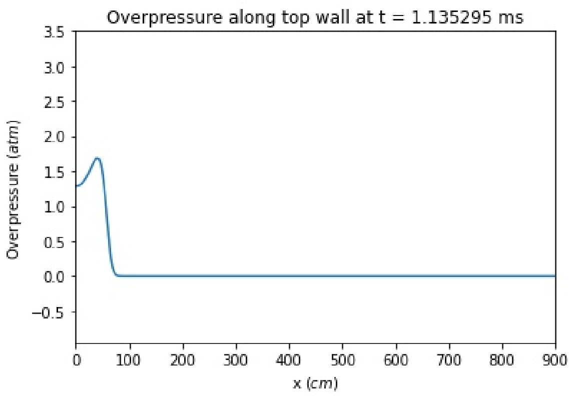
Table 1: Location of outflow vents (midpoint) and maximum overpressures

Name	x-coordinate (cm)	y-coordinate (cm)	Maximum overpressure (atm)
A	0.0	26.37	7.3
B	8.78	0.0	7.06
C	889.45	112.5	14.04
D	900.0	56.25	16.32

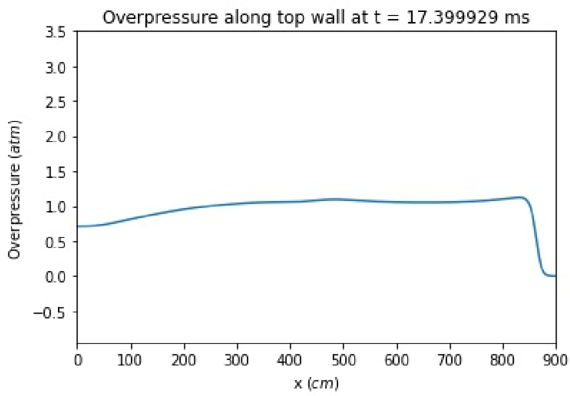
3.2 Three-dimensional results

The 2D results, though not realistic, provide a qualitative picture of the flow field. The 3D computations can be used to provide a quantitative picture of the overpressures that would be observed within the muffler. Similar to the 2D computations, the high-pressure flow from the detonation tube expands before being reflected off the top and bottom walls ($y = 0$, $y = H$). The flow field then evolves into an essentially 1D shock until it reflects off the back wall ($x = L$). Fig. 3a shows that the expanding high-pressure gas from the DT reflects off the top wall with an overpressure of 1.6 atm. The flow then evolves into an essentially 1D shock with an overpressure of about 1.1 atm (Fig 3b). Since we are solving the Euler equations, diffusion and boundary layer effects are not taken into account in these computations. We anticipate that these diffusion effects would reduce the maximum overpressures. Thus, the values obtained from our computations provide a maximum estimate of the pressure loads on the walls of the muffler.

Fig. 3c shows that the overpressure after the first wall reflection (off $x = L$) is around 3.2 atm. From Fig. 3d, we see that it takes around 10 ms for the ovepressures to drop down to 2 atm near the middle of the domain. Finally, Figs. 3e and 3f show the peak overpressure obtained after the second and third reflections (3 atm and 2.5 atm respectively). Through Fig. 3, we have obtained values for the peak overpressures that are realistic. Further, we have also determined for how long the high-pressure persists. This allows us to estimate the forces and stresses on the muffler wall which are necessary to determine the thickness of the walls and choice of material. Since the sound intensity is directly proportional to the overpressures, we can use details of the flow field to develop sound mitigation strategies.



(a)



(b)

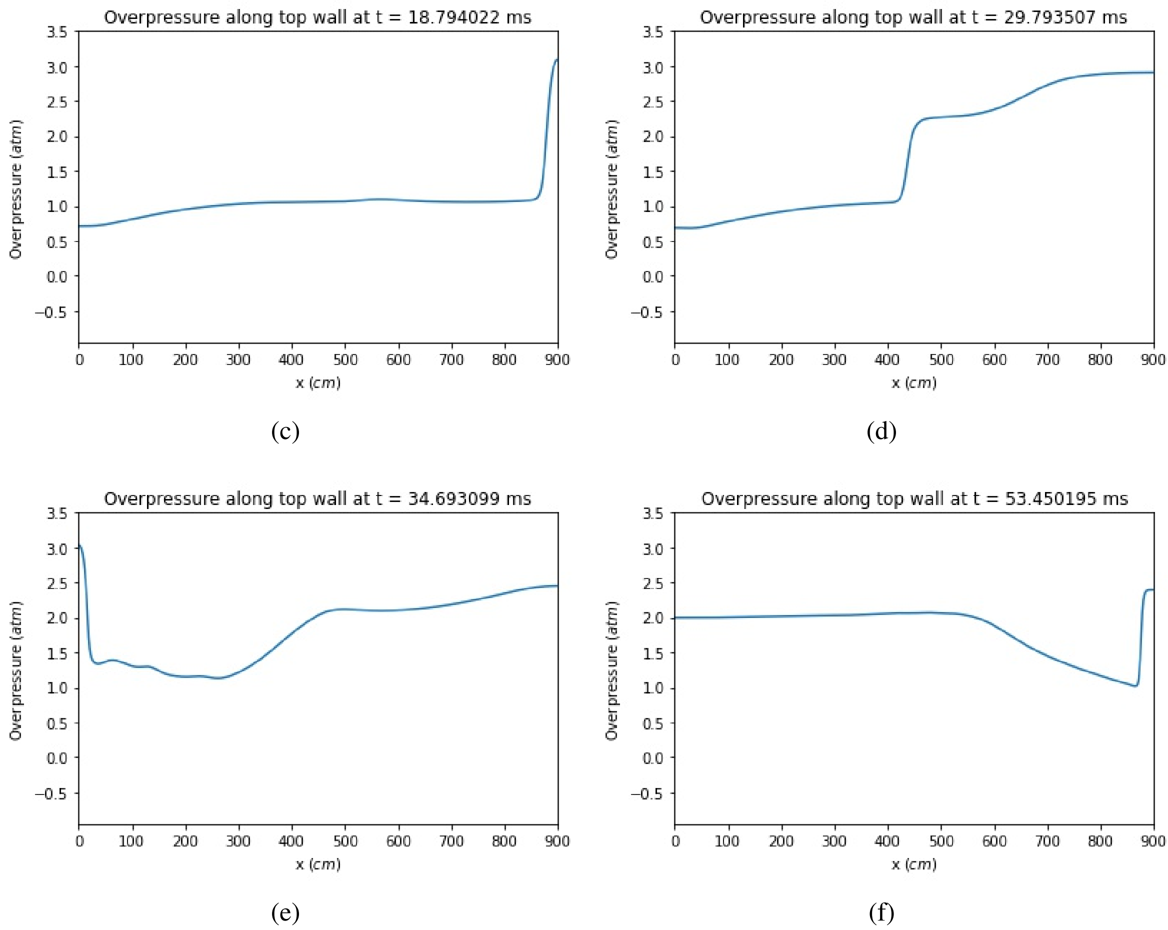


Figure 3: Overpressure at different time along x-axis (at $y = H$, $z = 0.5W$)

4 Conclusions

This work has studied the flow-field, and specifically the overpressures associated with a muffler design for a detonation tube. The unsteady, 2D Euler equations were solved for a scaled-down muffler design which showed that exit vents far away from the inlet (Cases C & D) experience higher maximum overpressures than vents that are closer to the inflow (Cases A & B). 3D computations were then carried out to estimate values for the overpressure in the muffler. These showed that the flow evolved into an essentially 1D shock and maximum overpressures were obtained immediately post the first reflection. These results provide the first step towards designing effective sound mitigation strategies for large-scale detonation tubes. Possible measures would include using baffles to break up the one-dimensional shock and using special material to absorb some of the pressure energy before venting out the gas into the atmosphere. Further details on how these computations aided the design process of the DRTF would be provided in the final talk.

5 Acknowledgements

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