

Numerical Investigation of Ram Accelerator Operation with Axisymmetric Projectiles

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Abstract

Numerical Investigation of Ram Accelerator Operation with Axisymmetric Projectiles

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The ram accelerator is a hypervelocity chemical propulsion device capable of accelerating massive projectiles throughout the velocity range of 0.5 km/s to 6.0 km/s. Its propulsion cycle is similar to that of an in-tube ramjet operating with subsonic, supersonic, and/or mixed mode combustion processes that are dependent on in-tube Mach number and projectile geometry. The projectile carries no onboard propellant and has no moving parts. Ram accelerator was originally successfully developed with finned-projectiles in smooth-bored tube. More recently, however, new configurations are being developed to operate with axisymmetric projectiles in baffled and railed tubes to implement more practical setup for various applications.

First, a review of theoretical and experimental developments of ram accelerators with emphasis on development of baffled and railed tubes is presented. Second, reviews of recent numerical/computational fluid dynamic models of railed and baffled tubes configurations are summarized. Then, some recommendations are provided for future works to improve CFD modeling of railed and baffled tubes with an expectation to layout a process how to optimize geometrical features of ram accelerators and projectiles. Lastly, a high-level summary of findings on railed and baffled tube CFD research works are provided. Achieving these research goals will improve our understanding of ram accelerators and provide guidance on how to optimize geometrical features of ram accelerators.

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Nomenclature

Variables

a	=	speed of sound
A	=	area
A_b	=	projected baffle surface area
C_d	=	coefficient of drag
C_{ED}	=	eddy-dissipation empirical constant
C_p	=	specific heat at constant pressure
D	=	baffle drag
D_{ED}	=	eddy-dissipation empirical constant
d_p	=	projectile diameter
d_c	=	chamber inner diameter
d_{eff}	=	effective bore diameter
E_a	=	Activation energy
F	=	projectile thrust
h	=	sensible enthalpy
I	=	non-dimensional thrust
κ	=	turbulence kinetic energy
M	=	Mach number
$M_{w,i}$	=	molecular weight of species i
$\nu'_{i,r}$	=	stoichiometric coefficient for reactant i in reaction r
$\nu''_{i,r}$	=	stoichiometric coefficient for product i in reaction r

P	=	pressure
Q	=	non-dimensional heat release parameter
Δq	=	heat release due to chemical reaction
$\mathfrak{R}$	=	universal gas constant
R	=	gas constant of the mixture
Re	=	Reynolds number
T	=	temperature
t_b	=	baffle thickness
u	=	flow velocity
V_b	=	baffle volume
V_c	=	chamber volume
V_{CJ}	=	Chapman-Jouguet detonation velocity
w_c	=	chamber width
$[X]_y$	=	molar concentration of species X with rate exponent y
Y_ξ	=	mass fraction of a particular reactant, ζ
Y_P	=	mass fraction of any product species

Greek

α	=	cone angle
β	=	geometrical constant
γ	=	specific heats at constant pressure per constant volume for a mixture
ε	=	turbulence kinetic energy dissipation rate

ζ	=	temperature-exponent in Arrhenius rate
μ	=	dynamic viscosity
ζ	=	species
ρ	=	density
σ	=	rate of reaction
χ	=	mole fraction
ω	=	specific dissipation rate

Subscripts

Arrhenius	=	pre-exponential factor in Arrhenius rate
CJ	=	property at Chapman-Jouguet state

Abbreviations

BTRA	=	baffled tube ram accelerator
EDC	=	eddy-dissipation concept
LES	=	large eddy simulation
MCRA	=	mechanically choked ram accelerator
RTRA	=	railed tube ram accelerator
SBRA	=	smooth bore ram accelerator
SDRA	=	superdetonative ram accelerator
TCRA	=	thermally choked ram accelerator

1. Introduction and Background

Ram accelerators are a novel chemical propulsion device capable of accelerating projectiles from 0.5 km/s to 6.0 km/s that was introduced by researchers at University of Washington in the 1980s [1]. The ram accelerator propulsion cycle is similar to that of an in-tube ramjet operating with subsonic, supersonic, and/or mixed mode combustion processes, dependent on in-tube Mach number and projectile geometry [1] [2] [3]. Unlike rockets, ram projectiles carry no onboard fuel to attain hypersonic velocities. In addition, ram accelerators can effectively provide a more uniform acceleration profile than gas guns to enable direct launching of a wider range of payloads to space [4] [5]. They also have been considered for aeroballistics testing [6] and, more recently, for percussion drilling and boring applications [7]. As a result, diverse usage of ram accelerator makes it an attractive device to further explore and improve its capabilities.

1.1 Ram Accelerator Concepts/Configurations

Ram accelerators are stationary devices filled with gaseous fuel, oxidizer, and diluents (as needed) that propel projectiles to velocities much greater than what can be achieved with powder gun technology. The projectile is shaped like the center-body of a conventional ramjet as shown in Figure 1-top that diffuses the supersonic flow for peak ram compression in the annular region at the point of maximum projectile diameter, which establishes the minimum flow cross section and defines the projectile throat as shown in Figure 1-bottom. Unlike in a ramjet engine, where fuel is added to the air and the flow of reaction products is choked with a nozzle downstream of the combustion zone, the flow of reaction products in the ram accelerator is

thermally choked by heat release from subsonic combustion at the full tube area behind the projectile while it is operating in the subdetonative velocity regime; i.e., at velocities below the Chapman-Jouguet detonation speed (V_{CJ}) [8]. The thermal choking process stabilizes a normal shockwave on the aft-body that moves rearward as the in-tube Mach number (M) increases. This manner of operation is referred to as the thermally choked ram accelerator (TCRA) propulsive mode.

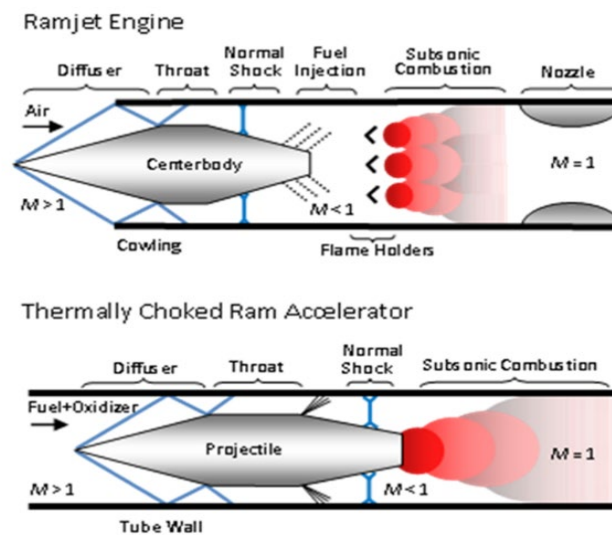


Figure 1 Top: air-breathing ramjet engine. Bottom: thermally choked ram accelerator.

The ram accelerator projectile is guided through the tube with integral fins on the projectile or rails protruding inward from the inner tube wall (Figure 2). The smooth bore ram accelerator (SBRA) utilizes projectiles with fins to minimize canting and keep them centered in the tube. The cross section of a SBRA configuration with aft-view of a finned projectile is shown in Figure 2-left. Extensive experimentation with finned-projectiles carried out in the 0.7 km/s to 2.6 km/s velocity range has shown that the SBRA is a robust and high-performance launcher [8] [9] [10] [11] [12] [13] with the potential for many applications [5] [6] [7].

In a railed-tube ram accelerator (RTRA), rails affixed to the inner tube wall guide axisymmetric projectiles down the center of the tube. The projectile aft-view and the cross section of a RTRA configuration are shown in Figure 2-right. The first experiments of this kind were carried out at the Institut de Recherches de Saint Louis (ISL) in France and were mostly focused on high Mach number operation at speeds greater than the V_{CJ} of the propellant, i.e., in the superdetonative velocity regime [14]. Many experiments in four-rail and five-rail tubes with 30-mm-diameter projectiles at entrance velocities greater than 1.7 km/s examined the operating characteristics of $H_2-O_2-CO_2$ propellant.

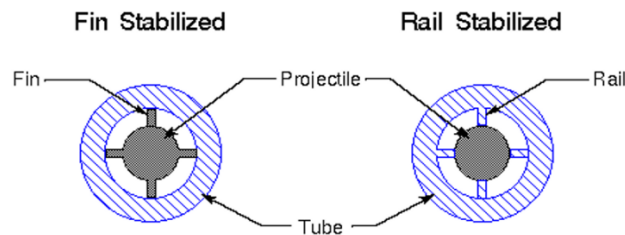


Figure 2 Projectiles centered in the ram accelerator tube. Left: smooth bore ram accelerator (SBRA) with a finned-projectile. Right: railed tube ram accelerator (RTRA) with an axisymmetric projectile.

Only two experiments at ISL in the subdetonative velocity regime in $CH_4-O_2-N_2$ propellant have been reported [15]. Operation in the velocity range of 1.30 km/s to 1.39 km/s over a distance of 3 m was demonstrated with the acceleration terminated by an unstart and abrupt projectile deceleration. A ram accelerator unstart is similar to that for an air-breathing supersonic diffuser, i.e., it results in a normal shockwave being pushed ahead of the diffuser with subsonic flow over the nosecone and the cessation of thermal choking [9] [10]. The peak operating velocity of 1.39 km/s in the RTRA at ISL was much lower than that of the SBRA under similar test conditions

[1] [2] [9] [10] [11] [12], which may be the reason why this line of research was discontinued after only two experiments. Renewed interest in RTRA technology has arisen for applications where high firing rates are required [7] [16] because axisymmetric projectiles are simpler to manufacture and have logistical advantages.

The theoretical thrust vs. Mach characteristics of the SBRA configuration operating in the TCRA propulsive mode predict quite well the multistage performance of a 38-mm-bore ram accelerator, as shown by the experimental velocity-distance data in Figure 3, which supports the assumption that the end state of the propulsive cycle is indeed thermally choked [17]. In this particular experiment, an 80-g accelerator projectile accelerated from 1.1 to 2.6 km/s in a 16-m-long test section. By developing a means that enabled operation in highly energetic propellants, the ram accelerator thrust could be nearly tripled using same fill pressure, resulting in much higher velocities in shorter barrels as indicated by the “Max Energetic Mixture” velocity-distance curve in Figure 3.

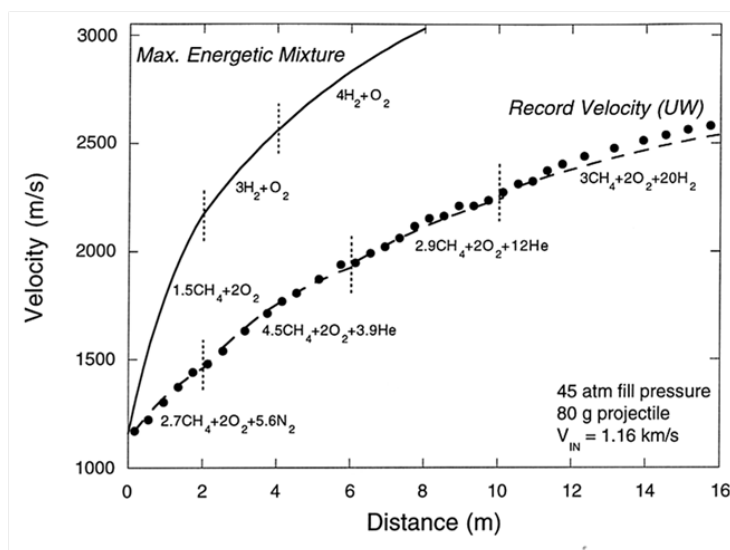


Figure 3 SBRA configuration operating in the TCRA propulsive mode accelerated an 80-g projectile to 2.6 km/s in a 38-mm-bore tube using multiple stages. Operation with maximum energetic propellants would result in nearly three times the thrust.

There are three main issues that reduce the performance capabilities of smooth bore ram accelerator. First, based on empirical results, heat release of the propellant must be reduced to $\sim 1/3$ of which is available (by adding diluents), which leads to thrust levels of only $\sim 1/3$ of the theoretical maximum in order to establish stable operation. When propellants with larger heat release (less diluent) are used, an undesirable situation arises in which the driving combustion wave surges past the projectile, causing a diffuser unstart [9] [10]. Second, high acceleration performance requires relatively high propellant fill pressure that results in extreme pressure spikes because in normal operation the thermally choked ram accelerator (TCRA) propulsive mode generates pressure ratios of 10-20 times the fill pressure (depending on in-tube Mach). The resulting high pressure at the base of the projectile exerts significant loads on both the projectile and launch tube [18]. Third, experiments showed that the peak velocity of the thermally choked propulsive mode was significantly reduced in a smooth bore tube when stabilizing fins were extended into the projectile throat region (point of maximum projectile cross-section). Similar peak velocity reductions in a ram accelerator using axisymmetric projectiles in a tube having sidewall rails were observed in ISL experiments [19].

To address these performance-limiting issues, the novel concept of baffled tube ram accelerator (BTRA) was first introduced by Higgins et. al., [20]. A section view of a representative BTRA design with an axisymmetric projectile is shown in Figure 4.

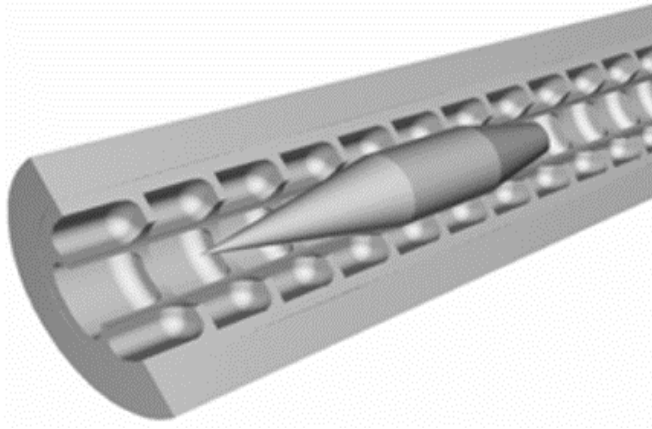


Figure 4 Baffled tube ram accelerator configuration with an axisymmetric projectile.

These annular baffles are like washers that protrude from the inner wall of the tube. These baffles bound chambers that extend to the inner wall of the tube. Flow field phenomena arising as the projectile enters the baffled tube are illustrated in Figure 5. This configuration enables the projectile to act as a one-way valve that can ingest reactive premixed fuel and oxidizer past its throat while preventing the combustion driven shock wave behind of the projectile from surging ahead into unburned propellant. Since these baffles prevent diffuser unstart, chamber-to-projectile diameter ratio can be increased to allow successful diffuser “start” at Mach numbers less than two while using more energetic propellant. To assure in-bore stability when rails are not used in the BTRA, the cylindrical shoulder of the projectile should span at least two baffles at all times.

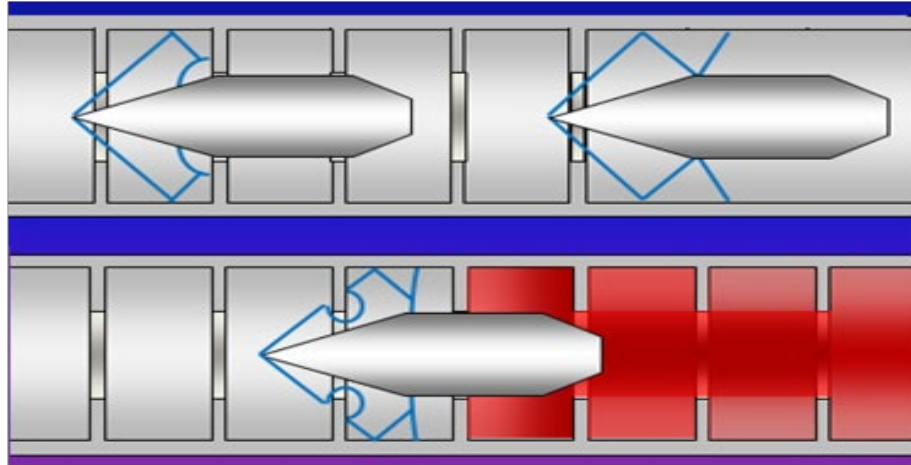


Figure 5 Propellant is ram compressed via area contraction and shock waves in annular chamber around projectile shoulder. Baffles prevent combustion behind projectile from driving pressure waves ahead of shoulder.

The BTRA concept has the potential to triple the thrust performance of the conventional SBRA while operating at same fill pressure and can reduce its minimum starting Mach number and velocity by at least 25% [21]. In principle, this new launcher can accelerate axisymmetric projectiles with masses ranging from grams to metric tons up to velocities of approximately 3 km/s. Its low starting velocity potential allows consideration of a wide range of pre-launcher technologies that may greatly reduce the overall cost and operational complexities of hypervelocity launch systems for any application. In addition, the axisymmetric projectile geometry is favorable for railed-tube ram accelerators proposed for direct space launch applications at velocities greater than 4 km/s [5]. Thus, in addition to its high thrust at low Mach potential, the BTRA offers a significant advancement in ram accelerator technology for any application where axisymmetric projectiles are preferred.

Although the baffled tube concept offers a means to mitigate the three limitations of smooth bore ram accelerator (SBRA) operation previously discussed, the BTRA still has two main

operational velocity limits. First, for a given projectile geometry and BTRA configuration, there is a minimum entrance Mach number that allows the projectile to pass supersonically throughout the length of the baffled tube. The conditions under which this occurs are complicated because the axisymmetric projectile unstarts; i.e., pushes a normal shock ahead of it, as its shoulder leading edge approaches each baffle, as shown in Figure 5-top. The geometric parameters of BTRA must be such that the shockwave axial speed decays rapidly enough as it expands into the subsequent baffle chamber to allow the projectile shoulder to overtake the weakened shock before entering the next baffle. If the projectile Mach number is sufficiently high for a given BTRA configuration, then in this manner the projectile can remain started at the entrance to each baffle; i.e., maintain supersonic velocity with respect to the quiescent propellant. Second, when the strength of the shock wave generated by the leading edge of the projectile shoulder is too large as it just enters a chamber, it will initiate a detonation wave that travels forward and upstream through the next chamber, resulting in an unstart and cessation of thrust. A theoretical and computational modeling effort is underway to develop means to predict these two operational limits.

Optimizing the BTRA design requires understanding of how geometric variables of an axisymmetric projectile and baffled tubes impact its minimum starting velocity and operating characteristics at high Mach number. The following geometric variables are shown in Figure 6 for an axisymmetric projectile traveling in a baffled-tube section.

- 1) Baffle chamber diameter (d_c)
- 2) Baffle bore diameter (d_{bore})
- 3) Baffle thickness (t_{baffle})

- 4) Baffle chamber width (w_{chamber})
- 5) Baffle-chamber fillet radius (r_{chamber})
- 6) Projectile diameter ($d_{\text{projectile}}$)
- 7) Projectile nose angle (α_{nose})
- 8) Projectile tail angle (α_{tail})
- 9) Projectile shoulder length (l_{shoulder})
- 10) Projectile base diameter (d_{base})
- 11) Baffle insert length ($l_{\text{baffle insert length}} = w_{\text{chamber}} + t_{\text{baffle}}$)

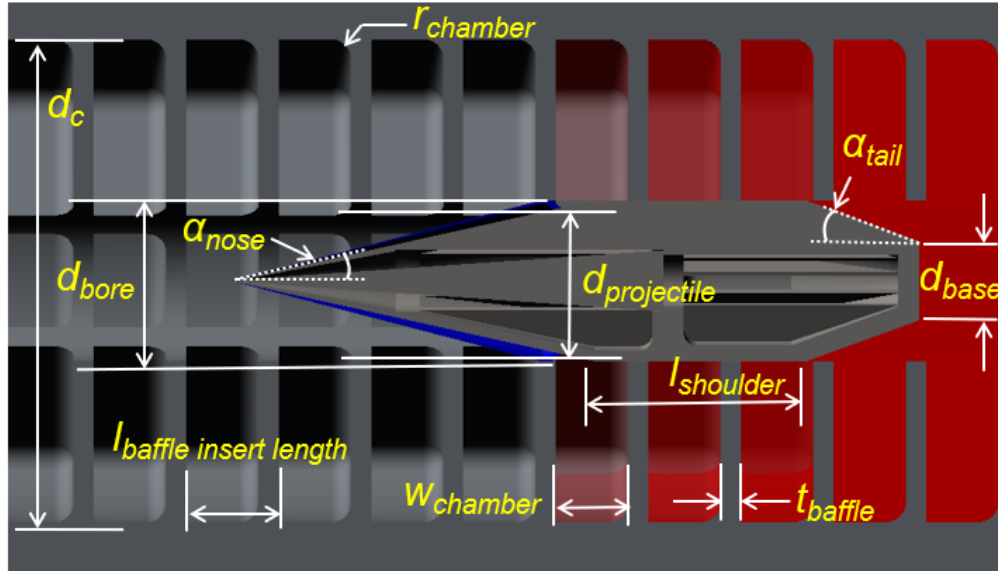


Figure 6 An axisymmetric projectile and BTRA geometric parameters.

BTRA configurations are not limited to “normal baffle” setups; i.e., where washer-like baffles are perpendicular to the direction of projectile travel. Baffles inclined in a ramp-like fashion, i.e.; “slanted baffle,” are another geometric variation for BTRA optimization that is currently being investigated at University of Washington [22].

In ram accelerator operation, whether it is SBRA, RTRA, or BTRA, the net result of any propulsive mode is the establishment and stabilization of a high-pressure region on the projectile body that provides thrust, which is directly proportional to the propellant fill pressure. Therefore, for a given projectile design, the ram accelerator propellants and fill pressures can be tailored to provide the preferred acceleration profile for any application. The acceleration range can be categorized to three classes; i.e., 1) high-g applications (10,000+ g) for insensitive payloads, 2) medium-g applications (500 g – 5,000 g) for some electromechanical payloads, and 3) low-g applications (3 g – 100 g) for sensitive electronics and/or biological payloads. The acceleration tailoring capability of ram accelerator makes this device attractive for many applications at nearly any size scale.

1.2 Ram Accelerator Velocity Regimes and Operating Modes

Ram accelerator propulsive modes take on distinctive characteristics dependent on the velocity of the projectile relative to the propellant V_{CJ} [1] [8] [23] [24] [25]. In the subdetonative velocity regime, projectile velocity is less than V_{CJ} and the combustion process is typically subsonic relative to the projectile. When the projectile has a cone frustum aft-body, combustion in the TCRA propulsive mode is stabilized behind the projectile by means of thermal choking at full tube area somewhere farther downstream, as shown in Figure 7.

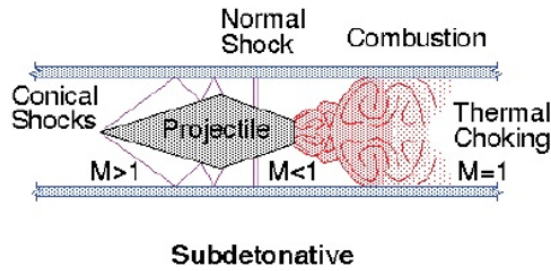


Figure 7 Thermally choked ram accelerator mode operating in subdetonative velocity regime ($V_p < V_{CJ}$).

When the ram accelerator projectile has a center-body with a flow constriction on its aft-end, as shown in Figure 8, subsonic combustion can be stabilized in its midsection. The flow of combustion products is then mechanically choked by the exit nozzle and expanded supersonically back to full tube area. With a fixed nozzle-to-tube area ratio, the exit Mach number is constant at all operable flight Mach numbers. This propulsive cycle is referred to as the mechanically choked ram accelerator (MCRA) mode, which operates primarily in the subdetonative velocity regime.

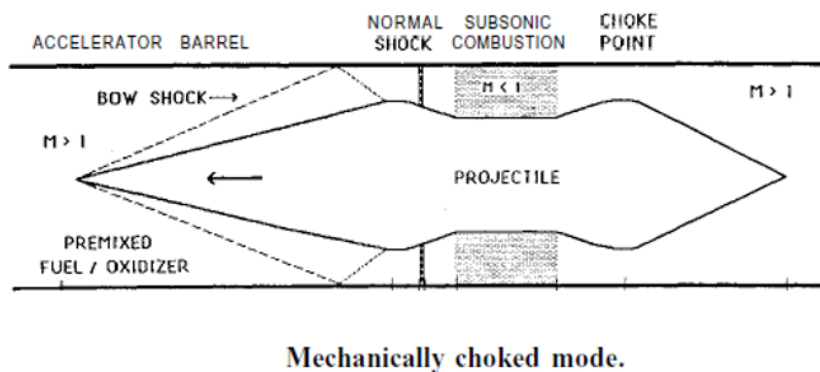


Figure 8 Mechanically choked ram accelerator mode operating in subdetonative velocity regime ($V_p < V_{CJ}$).

The projectile nose cone angle is such that the oblique shock system in the diffuser (from nose cone to maximum projectile diameter) does not initiate combustion throughout its operable

Mach number range. The flow slows down over the nose cone as it approaches the projectile throat, and then accelerates supersonically in the divergent region behind it until it passes through the normal shockwave that is located downstream. In the TCRA mode (Figure 7) the combustion zone is established behind the projectile and thermally chokes the flow, which thereby stabilizes the normal shock on the projectile. The thermal choking region also isolates the projectile from any flow disturbances occurring farther downstream.

In the MCRA mode (Figure 8), the combustion zone is totally within the projectile midsection and is fully subsonic. A convergent-divergent nozzle serves to choke the exhaust flow and maintain the normal shock in the unreacted propellant behind the projectile throat. In both propulsive modes, combustion is initiated by either an onboard ignitor and/or interaction with compressed residual launch tube gases [26].

In the superdetonative velocity regime where the projectile velocity is greater than V_{CJ} , all of the combustion heat release occurs supersonically in the annular region between the projectile body and tube wall [4] [27] [28] [29] [30]. The flow then expands supersonically back to full tube area. There are many different superdetonative ram accelerator (SDRA) propulsive modes distinguished by the combustion initiation and stabilization processes, three of which are described here; 1) overdriven detonation ram accelerator mode [1], 2) oblique detonation mode [8], and 3) shock-induced combustion [31] as shown in Figure 9, Figure 10, and Figure 11 respectively.

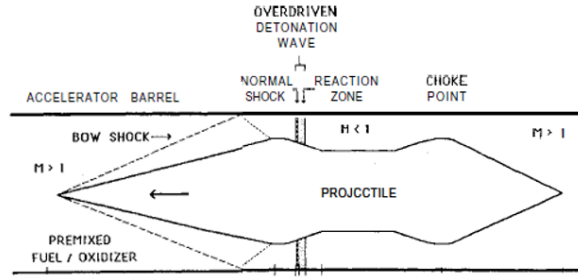


Figure 9 Overdriven detonation ram accelerator mode operating in superdetonative velocity regime ($V_p > V_{CJ}$) [1].

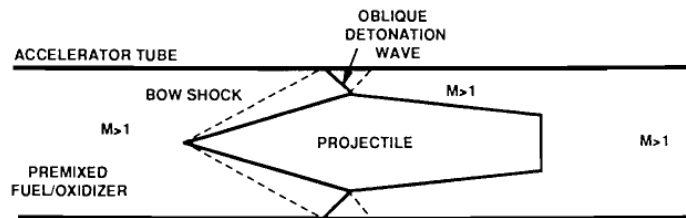


Figure 10 Oblique detonation ram accelerator mode operating at superdetonative velocity regime ($V_p > V_{CJ}$) [8].

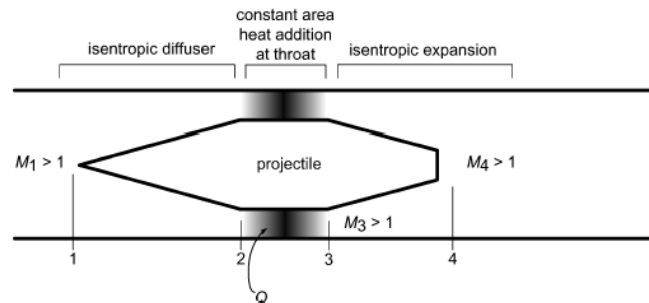


Figure 11 Shock-induced combustion ram accelerator mode operating in superdetonative velocity regime ($V_p > V_{CJ}$) [3].

Above velocities of approximately 3 (km/s), the ballistic efficiency drops off significantly in the TCRA propulsive even with hydrogen-based propellant mixtures [1] [8] [23] [24] [25]. Higher velocities are attainable, however, with the SDRA propulsive modes. In the three cases mentioned, the projectile velocity must exceed V_{CJ} . A transition to one of the detonation modes can be achieved by having an abrupt change of propellant mixture in the accelerator tube at the

appropriate location, using a thin diaphragm to separate the mixtures [3] [10] [21] [32]. If the second mixture is tailored to have a detonation speed sufficiently below the speed of the projectile, transition to one of the detonative modes occurs automatically; the specific mode depends on the projectile geometry.

In overdriven detonation mode (Figure 9), the projectile Mach number is sufficiently high for the normal shock to initiate combustion, which occurs in a very thin layer immediately behind the shock. The Mach number following heat release is subsonic; thus, the shock and reaction zone together establish an overdriven detonation wave. The region of increasing flow area behind the diffuser throat decelerates the flow subsonically to the projectile waist region. Thereafter the flow is accelerated through the converging entrance to the nozzle up to sonic velocity. The choking of the flow in the exhaust nozzle keeps the detonation wave overdriven, and expands the combustion products back to full tube area to a supersonic Mach number that is fixed by the area ratio and independent of flight Mach number. This projectile has a configuration similar to that of the MCRA projectile in that it also requires a nozzle to choke the exhaust flow. As a result, a projectile of this geometry can first be accelerated by the subsonic combustion mode and then by the overdriven detonation mode. The maximum velocity capability of the overdriven detonation mode is approximately 5 km/s [1].

In oblique detonation mode (Figure 10), the projectile nose cone angle, the projectile velocity, and the speed of sound of the mixture are tuned such that the initial conical shock does not initiate combustion, but the subsequent reflected shock does. In operation, the reflected shock becomes an oblique detonation wave. The projectile geometry is designed such that the reflected detonation wave strikes the projectile behind of the leading edge of the shoulder. The flow is then

expanded supersonically by the diverging rear of the projectile back to full tube area. The exit Mach number of this operating mode increases with increasing flight Mach number.

In the shock-induced combustion propulsive mode (Figure 11), the projectile nose cone angle is designed such that the combustion is not initiated by the initial compression process. Instead, combustion is initiated by one of several reflected shockwaves in the projectile throat region. The combustion process is decoupled from the shockwave(s) yet proceeds fast enough to go to completion on the projectile body with the flow of combustion products expanding supersonically back to the full tube area. The flow exit Mach number of this propulsive mode increases with increasing flight Mach number.

Although the TCRA propulsive mode is limited to projectile velocities below V_{CJ} , experiments have shown that the projectile can smoothly accelerate from velocities below to above V_{CJ} [8] [33]. This transition process from the subdetonative to superdetonative velocity regime is accomplished in the “transdetonative velocity regime,” where mixed propulsive modes which both subsonic and supersonic combustion processes occur on the body and behind the projectile, as shown in Figure 12.

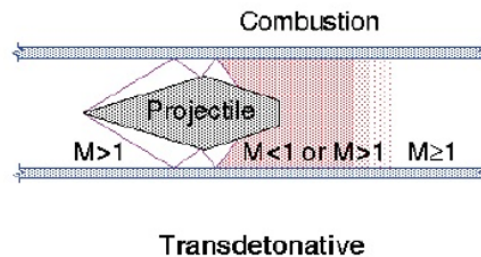


Figure 12 Ram accelerator operating at transdetonative velocity regime ($V_p \sim V_{CJ}$).

In experiments, it was observed that within a ram accelerator stage that is filled with a single propellant mixture, a projectile could make a transition from the TCRA mode to the superdetonative mode with continuous operation [8]. The projectile acceleration steadily decreased as it approached V_{CJ} and would then undergo a rapid increase in acceleration as its velocity-to-CJ speed ratio was in the range of $0.9 < V_p/V_{CJ} < 1.1$. In this transdetonative velocity regime, the projectile Mach number is sufficient that the shockwave train on the aft-body can ignite the propellant, achieving a mixed combustion mode combining the supersonic combustion with subsonic combustion processes. At higher velocities, the combustion process went to completion on the projectile body as it began to operate in one of the SDRA propulsive modes. Thus, the projectile can go beyond the limits of TCRA operation and eventually make a transition to the SDRA propulsive mode in the superdetonative velocity regime while operating within a single propellant.

1.3 Ram Accelerator Theoretical Model

Analyzing quasi-steady SBRA performance in the thermally choked ram accelerator propulsive mode can be achieved using one-dimensional flow assumptions and applying conservation of mass, momentum, and energy to a control volume that contains the projectile. Quasi-steady and unsteady one-dimensional modeling of the TCRA in a SBRA showed that in the Mach number range of 3 to 4, thrust estimates of the unsteady one-dimensional model agreed with the experimental results [34]. For reference purposes, this quasi-steady model is briefly described here. The details of unsteady one-dimensional modeling are shown by Bundy et al. [18], Bauer et al. [35], and Bengherbia [36].

The one-dimensional quasi-steady flow field model for the TCRA propulsive mode operating in a SBRA can be described in the context of a control volume drawn around the projectile as shown in Figure 13. The flow field is shown in the projectile's frame of reference. Supersonic propellant enters the control volume at State/Station (1) ahead of the projectile. Heat release occurs inside control volume and flow is thermally choked downstream ($M_2 = 1$) as it exits the control volume at State/Station (2).

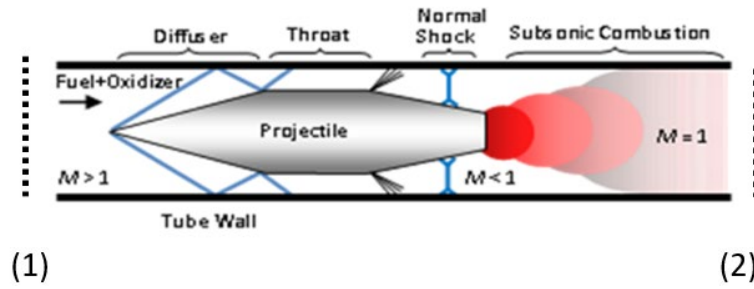


Figure 13 Control volume for TCRA thrust analysis.

To determine thrust generated at a given M_1 , equations for the conservation of mass, momentum and energy are applied between State (1) and State (2) as described below. Conservation of mass requires the mass flux entering and exiting the control volume to be the same as indicated by Equation 1, where ρ is the flow density, A is the cross-sectional area of SBRA and u is the one-dimensional flow velocity;

Equation 1

$$\rho_1 A_1 u_1 = \rho_2 A_2 u_2$$

Conservation of momentum in Equation 2 requires the difference between the sum of momentum flux and static pressure, P , entering and exiting the control volume to be equal to the force F applied to the projectile;

Equation 2

$$P_1 A_1 + \rho_1 A_1 u_1^2 + F = P_2 A_2 + \rho_2 A_2 u_2^2$$

Conservation of energy requires the sum of energy flux entering the control volume and the heat release due to chemical reaction to be equal to the energy flux exiting the control volume as shown in Equation 3, where h is the sensible enthalpy and Δq is the heat release due to chemical reaction;

Equation 3

$$h_1 + \frac{1}{2} u_1^2 + \Delta q = h_2 + \frac{1}{2} u_2^2$$

The ideal gas Equation of State Equation 4, speed of sound Equation 5, enthalpy for calorically perfect gas Equation 6 and Mach number Equation 7 are sufficient to close this set of equations to derive a thrust-Mach number relationship for the TCRA. New variables in Equations 4-6 are; R is gas constant, T is the temperature, a is the speed of sound, γ is the ratio of specific heats, and C_p is the specific heat at constant pressure;

Equation 4

$$P = \rho R T$$

Equation 5

$$a = \sqrt{\gamma R T}$$

Equation 6

$$h = h(T)$$

Equation 7

$$M = \frac{u}{a}$$

The momentum equation (Equation 2) can be further modified using Equations 1, 4, 5 and 7 in terms of pressure ratio P_2/P_1 , density ratio ρ_2/ρ_1 , and non-dimensional thrust $F/(P_1A)$ as shown here in Equation 8 and Equation 9 ;

Equation 8

$$1 + M_1^2 a_1^2 \frac{\rho_1}{P_1} + \frac{F}{P_1 A_1} = M_2^2 a_2^2 \frac{\rho_2}{P_1} + \frac{P_2}{P_1}$$

Equation 9

$$\frac{P_2}{P_1} = \frac{M_1}{M_2} \sqrt{\frac{\gamma_1 R_2 T_2}{\gamma_2 R_1 T_1}}$$

Introducing a non-dimensional heat release parameter (Q) and using Equations 5-7 to rewrite conservation of energy (Equation 3) in terms of static temperature ratio T_2/T_1 , constant pressure heat capacity ratio C_{p2}/C_{p1} , and non-dimensional enthalpy $h/(C_p T)$, results in the following Equation 10, Equation 11, and Equation 12 ;

Equation 10

$$Q \stackrel{\text{def}}{=} \frac{\Delta q}{C_{p1} T_1}$$

Equation 11

$$\frac{h_1}{C_{p1} T_1} + \frac{\gamma_1 - 1}{2} M_1^2 + Q = \frac{h_2}{C_{p1} T_1} + \frac{\gamma_2 - 1}{2} M_2^2 \frac{C_{p2} T_2}{C_{p1} T_1}$$

Equation 12

$$\frac{T_2}{T_1} = \frac{C_{p1}}{C_{p2}} \left(\frac{\frac{h_1}{C_{p1} T_1} + \frac{\gamma_1 - 1}{2} M_1^2 + Q}{\frac{h_2}{C_{p1} T_1} + \frac{\gamma_2 - 1}{2} M_2^2} \right)$$

Defining I_{SBRA} to be non-dimensional thrust (Equation 13) and rewriting Equation 8 using Equation 9 and Equation 12 yields the following global quasi-steady thrust equation for the ram accelerator operating in any propulsive mode in a smooth bore tube;

Equation 13

$$I_{SBRA} \stackrel{\text{def}}{=} \frac{F}{P_1 A_1}$$

If flow is thermally choked at State (2); i.e., $M_2 = 1$, then Equation 14 can be rewritten as a non-dimensional thrust equation for the TCRA propulsive mode operating in a SBRA as shown here in Equation 15;

Equation 14

$$I_{SBRA} = \frac{M_1 \gamma_1}{M_2 \gamma_2} (1 + \gamma_2 M_2^2) \sqrt{\left(\frac{\gamma_2 - 1}{\gamma_1 - 1} \right) \left(\frac{\frac{h_1}{C_{p1} T_1} + \frac{\gamma_1 - 1}{2} M_1^2 + Q}{\frac{h_2}{C_{p1} T_1} + \frac{\gamma_2 - 1}{2} M_2^2} \right)} - (1 + \gamma_1 M_1^2)$$

Equation 15

$$I_{SBRA} = \frac{M_1 \gamma_1}{\gamma_2} (1 + \gamma_2) \sqrt{\left(\frac{\gamma_2 - 1}{\gamma_1 - 1} \right) \left(\frac{\frac{h_1}{C_{p1} T_1} + \frac{\gamma_1 - 1}{2} M_1^2 + Q}{\frac{h_2}{C_{p1} T_1} + \frac{\gamma_2 - 1}{2}} \right)} - (1 + \gamma_1 M_1^2)$$

Knowlen et. al., [21] showed that non-dimensional thrust for the TCRA propulsive mode operating in a SBRA can be correlated to the same propulsive mode operating in the BTRA. This required the introduction of a geometrical constant, β , that equates available baffle chamber volume for a given chamber-to-projectile diameter ratio, d_c/d_p (when $d_p = d_b$) baffle thickness, t_b , chamber width, w_c , chamber volume, V_c , and baffle volume, V_b , to an equivalent cylindrical volume in SBRA configuration with effective bore diameter d_{eff} . This constant β is illustrated in

Figure 14 and defined in Equation 16. Note that chamber volume, V_c , is the available volume inside each chamber without any volume occupied by supportive structure such as rail. For more information refer to Figure 45, Figure 46, and Figure 47.

Equation 16

$$\beta = \frac{1 + \left(\frac{w_c}{t_b}\right)}{1 + \left(\frac{w_c}{t_b}\right)\left(\frac{d_c}{d_p}\right)^2}$$

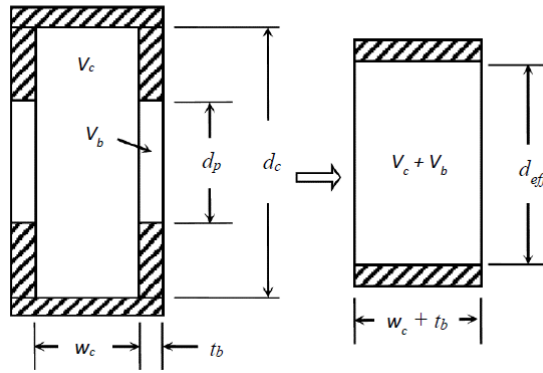


Figure 14 Geometrical constant, β , is a ratio that describes available volume of BTRA configuration to an equivalent volume in SBRA configuration.

The relation below, Equation 17, correlates the non-dimensional thrust of one-dimensional quasi-steady SBRA to BTRA configuration [21].

Equation 17

$$I_{BTRA} = \frac{I_{SBRA}}{\beta}$$

The one-dimensional quasi-steady flow field model for the TCRA propulsive mode operating in a BTRA can be described in the context of a control volume drawn around the projectile as shown in Figure 15.

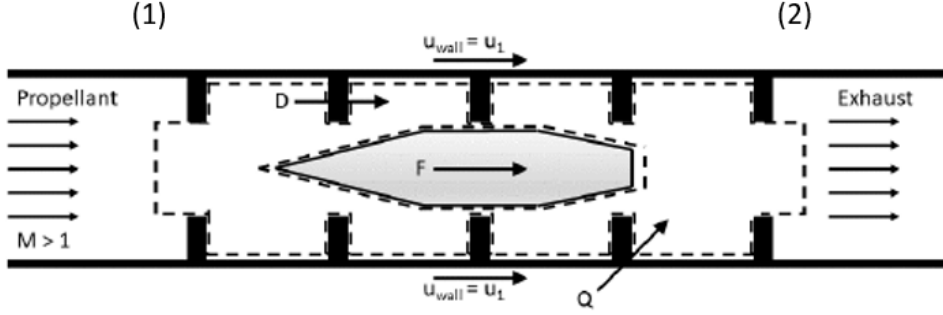


Figure 15 BTRA flow field in projectile frame of reference. Supersonic propellant enters the control volume at State (1) ahead of the projectile. Heat release occurs inside control volume and flow is thermally choked downstream ($M_2=1$) and exists at State (2).

Similar to SBRA configuration, one can write conservation of mass, momentum and energy equations are applied between State (1) and State (2) for BTRA. In the context of BTRA, baffle “drag” refers to the force applied in the direction of projectile motion to the baffles, which diverts some of the thrust available for accelerating the projectile. Fully accounting for baffle drag in developing a quasi-one-dimensional model for the thrust-Mach performance characteristics of the BTRA is an ongoing theoretical and experimental effort [37]. Momentum and energy conservation equations in projectile frame of reference can be modified to reflect the effect of baffle drag. Momentum conservation equation (Equation 2) can be modified into Equation 18, in which D represents baffle drag. Also, the energy conservation equation (Equation 3) is modified to include work done on baffles by the drag force as shown in Equation 19 to yield a new non-dimensional thrust shown in Equation 20 [37] [38].

Equation 18

$$P_1 A_1 + \rho_1 A_1 u_1^2 + F + D = P_2 A_2 + \rho_2 A_2 u_2^2$$

Equation 19

$$\rho_1 A_1 u_1 (h_1 + \frac{1}{2} u_1^2 + \Delta q) + D u_1 = \rho_2 A_2 u_2 (h_2 + \frac{1}{2} u_2^2)$$

Equation 20

$$I_{BTRA} = \frac{M_1 \gamma_1}{\gamma_2} (1 + \gamma_2) \sqrt{\left(\frac{\gamma_2 - 1}{\gamma_1 - 1} \right) \left(\frac{\frac{h_1}{C_{p1} T_1} + \frac{\gamma_1 - 1}{2} M_1^2 + Q + \frac{D(\gamma_1 - 1)}{P_1 A_1 \gamma_1}}{\frac{h_2}{C_{p1} T_1} + \frac{\gamma_2 - 1}{2}} \right)} - (1 + \gamma_1 M_1^2) - \frac{D}{P_1 A_1}$$

By introducing baffle projected area as the surface drag acts upon, one can introduce a definition for the drag, as shown in Equation 21, in which A_b is the projected baffle surface area, C_d is the baffle drag coefficient and n_c is the number of chambers that the combustion zone actively affects [21].

Equation 21

$$D = C_d \rho_1 A_b n_c |u_1 - u_2| (u_1 - u_2)$$

Determining the numerical value for C_d and the number of chambers influenced by the combustion zone are some of the objectives of on-going theoretical, computational, and experimental efforts at University of Washington [21] [22] [37].

1.4 Ram Accelerator Operational Limits

The experimental operational limits of ram accelerator, in general, are not well predicted using one-dimensional flow theoretical model assumption. Nonetheless, three operational limits and their characteristics were identified by Higgins et al., [9] [10] without any a priori flow dimensionality assumption. These limits to ram accelerator operation are functions of projectile

geometry (projectile diameter at the throat and base diameter), Mach number, and heat release that form a theoretical operational envelope as shown in Figure 16.

The first limit is a minimum operational Mach number that is required to prevent isentropic flow from choking at the projectile throat, identified as “Sonic at Throat” in Figure 16. In a SBRA, the projectile must enter the propellant at velocities above this minimum Mach number to enable gas dynamic starting; i.e., having the flow in the throat be greater than or equal to sonic velocity. Note, experiments with inert gases have been used to measure the minimum Mach number by letting the projectile supersonically coast down to the point where it unstarts, as indicated in the data by a sudden increase in drag.

The second operational Mach number limit depends on heat release as indicated by the curved labeled “Shock at Throat” in Figure 16, which is defined as the Mach number where the normal shock wave is predicted to be located at the projectile throat for a given amount of heat release. If the heat release is increased, this limiting Mach number must increase to keep the shockwave from being pushed forward through the throat [28] [37].

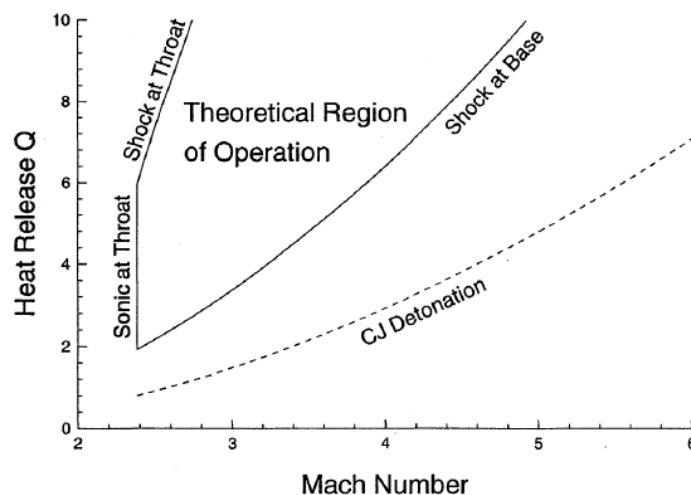


Figure 16 Theoretical operation of ram accelerator [9] [10].

The third operational Mach number limit depends on projectile base area and combustion heat release as indicated by the “Shock at Base” curve in Figure 16. This limit corresponds to the maximum Mach number at which a given heat release can support a normal shockwave on the base of the projectile in ideal flow. In principle, once the projectile reaches this limiting Mach number, the thrust then drops to zero, resulting in a chugging projectile with no further velocity gain. In practice, once propellant is ignited and combustion stabilized with the projectile, the ideal normal shockwave is actually a shockwave train that remains attached to the projectile base well above this theoretical limit. When entering at a Mach number that is too low to ignite a particular propellant, the shockwave falls off the projectile and it decelerates supersonically until the Mach number corresponding to the Sonic-at-Throat limit is reached and an unstart occurs [26].

The operational limits based on experimental results are different from those predicted by theory as shown in Figure 17. Boundary “a” is the heat release limit that results in an abrupt unstart upon entrance to a ram accelerator stage with too energetic of propellant. Boundary “b” is based on the heat release limit that results in an unstart after at least 1 m of distance traveled. In this scenario the shockwave takes a finite time to move forward toward the projectile throat upon entering the propellant. This transition time increases as the heat release decreases resulting in larger velocity gains before unstart and, thus, a negative slope in the Q - M plane. Boundary “c” is the Mach number limit for unstarts occurring after the projectile reaches a certain fraction of the CJ speed that primarily depends on projectile material. Finally, boundary “d” represents the minimum heat release at which ram accelerator operation can be initiated and stabilized.

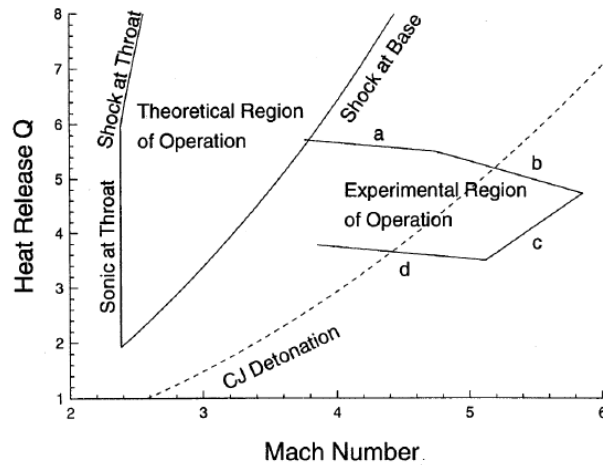


Figure 17 Theoretical versus experimental operation of ram accelerator [9] [10].

The operating envelope shown in Figure 17 indicates that; 1) a minimum Mach number must be achieved to prevent an unstart due to inert gas dynamic effects, 2) a minimum propellant heat release must be exceeded to sustain ram acceleration, and 3) the propellant heat release must remain below the maximum at which unstarts will occur. As a result, in order to accurately predict the operational envelope of a ram accelerator, high-fidelity computational fluid dynamics (CFD) simulations are required to provide a deeper understanding of flow fields in ram accelerators and how they influence the limits of operation.

1.5 Railed Tube Ram Accelerator Experiments

Renewed interest in RTRA technology has arisen for applications where high firing rates are required [7] [16] because axisymmetric projectiles are simpler to manufacture and have logistical advantages. The ongoing RTRA research at the University of Washington includes both experimental and CFD efforts. Experimental results have shown successful operation in a 38-mm-

bore, 2-m-long test section with railed-inserts and methane-air propellant in the velocity range of 1.0 km/s to 1.38 km/s [39]. In these experiments, a 2-m-long BTRA was used to accelerate axisymmetric projectiles to velocities greater than the minimum required to enter the RTRA without experiencing a Sonic-at-Throat unstart.

The non-dimensional thrust - Mach number curves predicted by Equation 15 have relative maxima at $M_1 \sim 3$ for the range of Q values shown in Figure 18 for a propellant with constant specific heat ratio $\gamma = 1.35$, $D = 0$, and $M_2 = 1$. At the maximum thrust Mach number, the exhaust flow is at rest in the laboratory frame of reference. The combustion products move backwards in the laboratory reference frame when M_1 is less than that at maximum thrust and in the direction of projectile motion at higher Mach numbers [2]. As Q increases, both the peak thrust and range of operational Mach number increase. The thrust is predicted to go to zero at the Q -dependent Mach number of the Chapman-Jouguet detonation wave for the propellant in all cases. The thrust predictions of this theoretical performance model agree well with SBRA experiments in many different propellants and bore sizes [8] [11] [12] [13]. This one-dimensional model has also been extended to account for real gas and unsteady flow effects with very good results [18] [40].

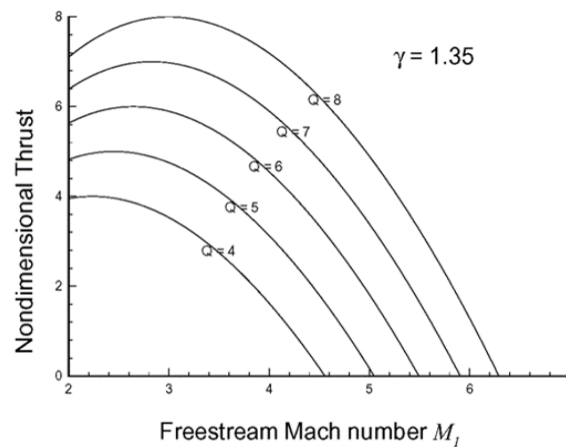


Figure 18 TCRA theoretical I - M_1 curves with non-dimensional heat release Q as a parameter.

Experiments have shown that presence of rails in RTRA significantly influences TCRA operation. The relatively consistent reduced thrust offset over the Mach number range of these experiments might be related to excessive total pressure losses from the stagnation region at the leading edge of the projectile shoulder and tube rails not accounted for in the theoretical 1-D model [39]. The experimental non-dimensional thrust vs. Mach number data and theory are plotted in Figure 19. Even though the experimental data are lower than theory, the trend for decreasing thrust with increasing Mach number is in good agreement. The experimental and theoretical thrust in SBRA experiments with this propellant are generally in much better agreement throughout most of the subdetonative velocity range, thus the rails significantly influence TCRA operation in a RTRA.

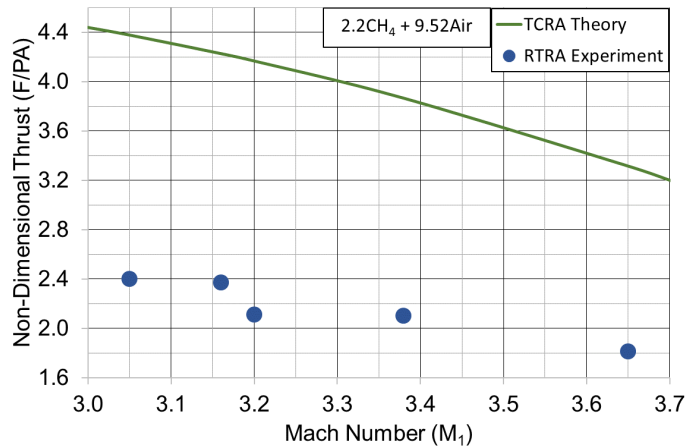


Figure 19 Theoretical and experimental non-dimensional thrust for $21 \text{ atm} < P_1 < 29 \text{ atm}$.

1.6 Baffled Tube Ram Accelerator Experiments

The ongoing BTRA research at the University of Washington includes both experimental and CFD efforts as well. Experimental results have shown successful operation in a 38-mm-bore, 2-m-

long test section with baffled tube-inserts and methane-air propellant in the velocity range of 0.8 km/s to 1.5 km/s and various fill pressures. Up to four sections of different baffled tube inserts can be assembled ahead of the launcher tube to create an 8-meter long BTRA configuration [41].

The non-dimensional thrust of 2 experiments and 4 CFD results at constant velocities is shown in Figure 20. The first experiment, i.e., HS2377, was conducted with a short shoulder projectile (158-gram) in $1.0\text{CH}_4+2\text{O}_2+4.3\text{N}_2$ mixture with 375 psig fill pressure and the second experiment (HS2378) was conducted with a slightly heavier projectile (206-gram) inside the same mixture at 450 psig. The first experiment shows the projectile moved from 1.0 to 1.2 km/s inside the baffled-tube#2 and then accelerated to a higher velocity of 1.4 km/s inside baffled-tube#3, while its non-dimensional thrust slightly increased from 6.1 to 6.6 unit. The baffled-tube#2 and #3 data from the first experiment are shown with light and dark blue circular symbols accordingly. The second experiment shows the projectile moved from 1.0 to 1.2 km/s inside the baffled-tube#2 and then accelerated to a higher velocity of 1.3 km/s inside baffled-tube#3, while its non-dimensional thrust slightly decreased from 5.6 to 4.5 unit. The baffled-tube#2 and #3 data from the second experiment are shown with light and dark green rectangular symbols respectively. The 4 CFD results with short shoulder projectile ran inside in $1.0\text{CH}_4+2\text{O}_2+4.67\text{N}_2$ mixture with 300 psig fill pressure at 1.0, 1.1, 1.2, and 1.4 km/s constant velocities shown with red triangular symbols in Figure 20. The non-dimensional thrust decreased as velocity increased similar to the second experiment, and its non-dimensional thrust decreased from 6.7 to 2.6 unit. A second order (red dotted curve) and a first order (orange dotted line) trend curves were applied to the CFD results to capture the trend for comparison. A full description of these 4 CFD results are documented Section#3 (CFD Modeling of Baffled Tube Ram Accelerator in Reactive Flow). Additional BTRA

experiments at University of Washington are still ongoing and will be compared against CFD results in future.

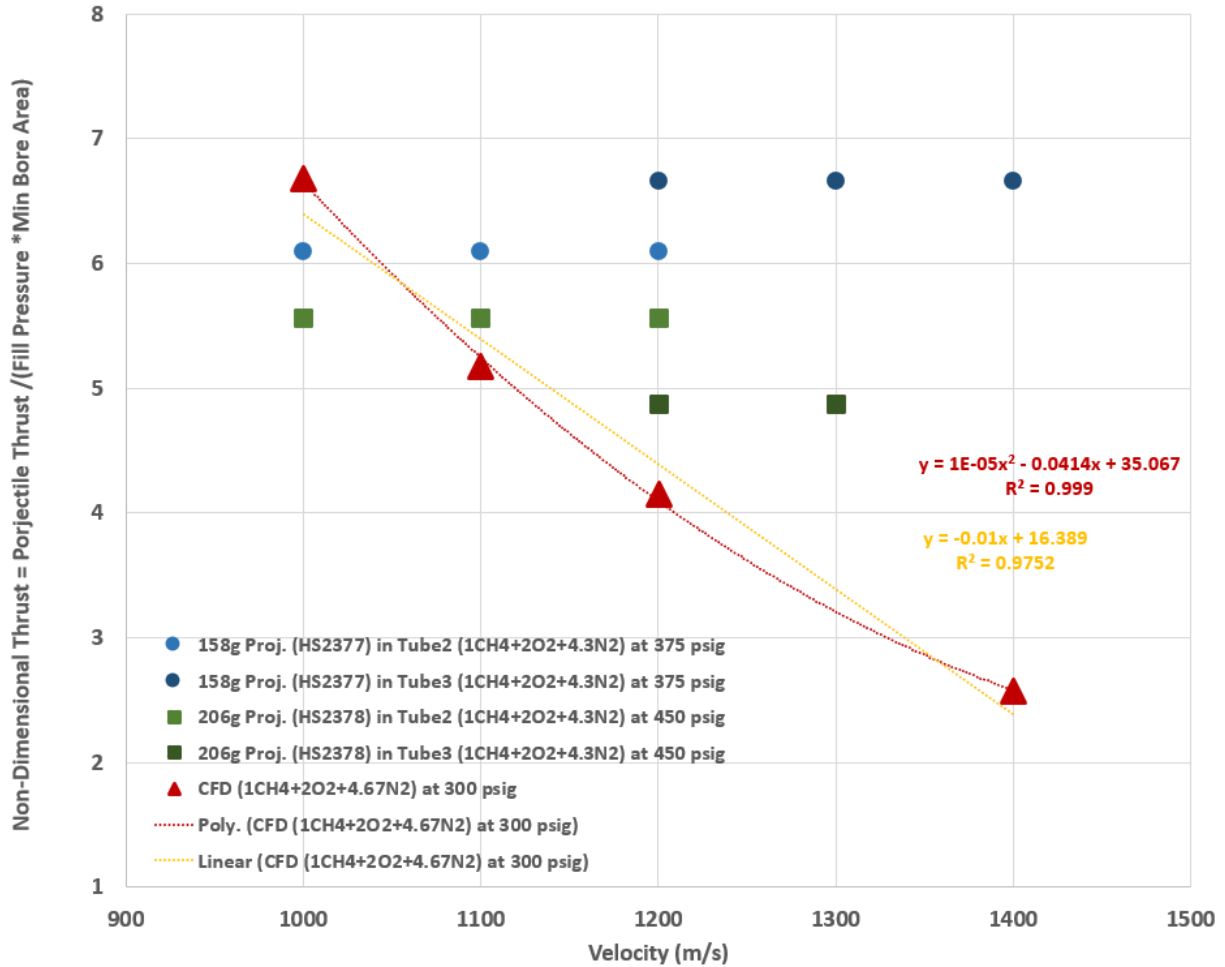


Figure 20 Non-dimensional thrust vs. velocity plot of HS2377 and HS2378 experiments against 4 CFD results at constant velocity

2. CFD Modeling of Railed Tube Ram Accelerator in Reactive Flow

Investigating the effects of rail-projectile interactions is one role of the CFD simulations currently in progress at University of Washington. Simulations of reactive flows with ANSYS Fluent software [42] reported in Section 2.1 (2.1 Development and Implementation of CFD Model for

RTRA Operation) investigated the transient flow field characteristics and thrust generation of the RTRA at constant velocities of 1.2 km/s and 1.4 km/s. Transient RTRA simulations were also carried out to determine the effects on thrust and shockwave stability due to projectile acceleration from an initial velocity of 1.4 km/s up to 1.5 km/s in a fixed time interval. These CFD results are reported in the Section 2.2 (2.2 CFD Modeling of RTRA at 1.2 km/s and 1.4 km/s) and Section 2.3 (2.3 CFD Modeling of RTRA at Constant Acceleration). An exploration of projectile geometry effects was subsequently carried out in which the throat and tail shape of the projectile were modified to determine if they would promote or suppress unstart behavior of the RTRA when operating at constant velocity of 1.4 km/s. These results are reported in Section 2.4 (2.4 CFD Modeling of RTRA with Projectile Modifications at 1.4 km/s).

2.1 Development and Implementation of CFD Model for RTRA Operation

CFD simulations carried out in a $1/8^{\text{th}}$ symmetry computational domain accounted for the presence of rails and an axisymmetric projectile. The outer surfaces of the CFD domain consisted of an inlet, an outlet, and the series of viscous walls (orange edges) and symmetry surfaces (purple edges) as shown in Figure 21. Ten normal to axis reference planes axially separated by one half of the projectile diameter were placed behind the projectile base to collect area and mass-averaged flow field quantities in the combustion zone. Instantaneous time history flow field properties, e.g., static pressure and temperature, were collected on the projectile, tube walls, and rails surfaces. The CFD tube wall pressures at the mid-channel symmetry plane were compared with experimental data obtained from similarly placed piezoelectric pressure transducers [39] [43].

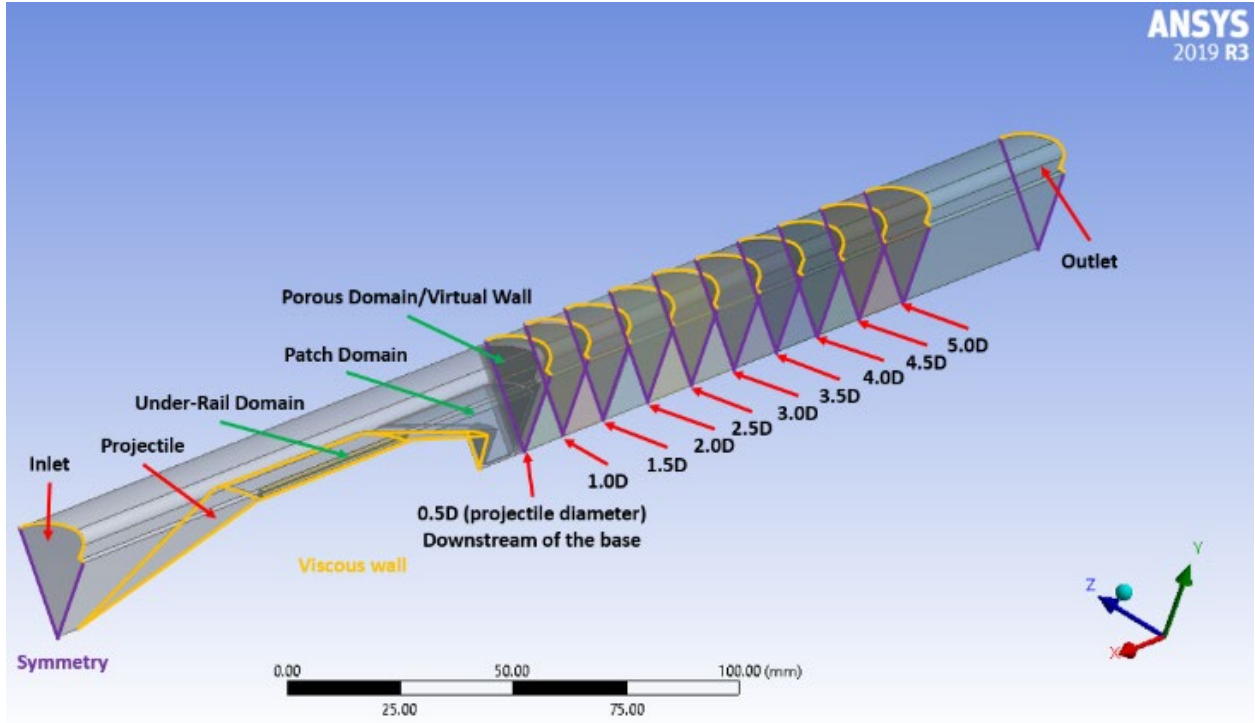


Figure 21 CFD domain with 1/8th symmetry for projectile and RTRA.

A patch domain placed behind the projectile base facilitated propellant ignition in subsonic flow with respect to the projectile. By this means, the propellant was numerically ignited and the sustainability of the combustion process was determined. A porous domain with high flow resistance characteristics placed behind the patch domain stabilized the combustion on the tail and base of the projectile before it was removed; i.e., the porous boundary condition was changed to the “interior” boundary condition a few hundred time-steps after the simulation began. The porous domain established a high pressure and temperature region behind the base of the projectile in a manner analogous to using a tube-obturator piston for starting the ram accelerator [26].

The CFD domain consisted of about 2.2 million cells/grids with isotropic tetrahedral unstructured volumetric grids with a maximum cell size of 0.762 mm. The isotropic characteristic

of the CFD domain provided an unbiased opportunity to establish combustion around the projectile and propagate in any direction as necessary. The boundary layer properties on viscous walls were determined with up to 10 layers of prism cells whose height grew smoothly by a rate of 1.2. The isotropic grid in RTRA is shown in Figure 22. In this figure, the three colored boxes are the grid regions for the insets shown Figure 23, Figure 24, and Figure 25. The red inset (Figure 23) shows details of grid quality around the inlet. The green inset (Figure 24) shows the gap region between the projectile shoulder and rail. The yellow inset (Figure 25) shows the grid region behind the base and around the patch and porous domain.

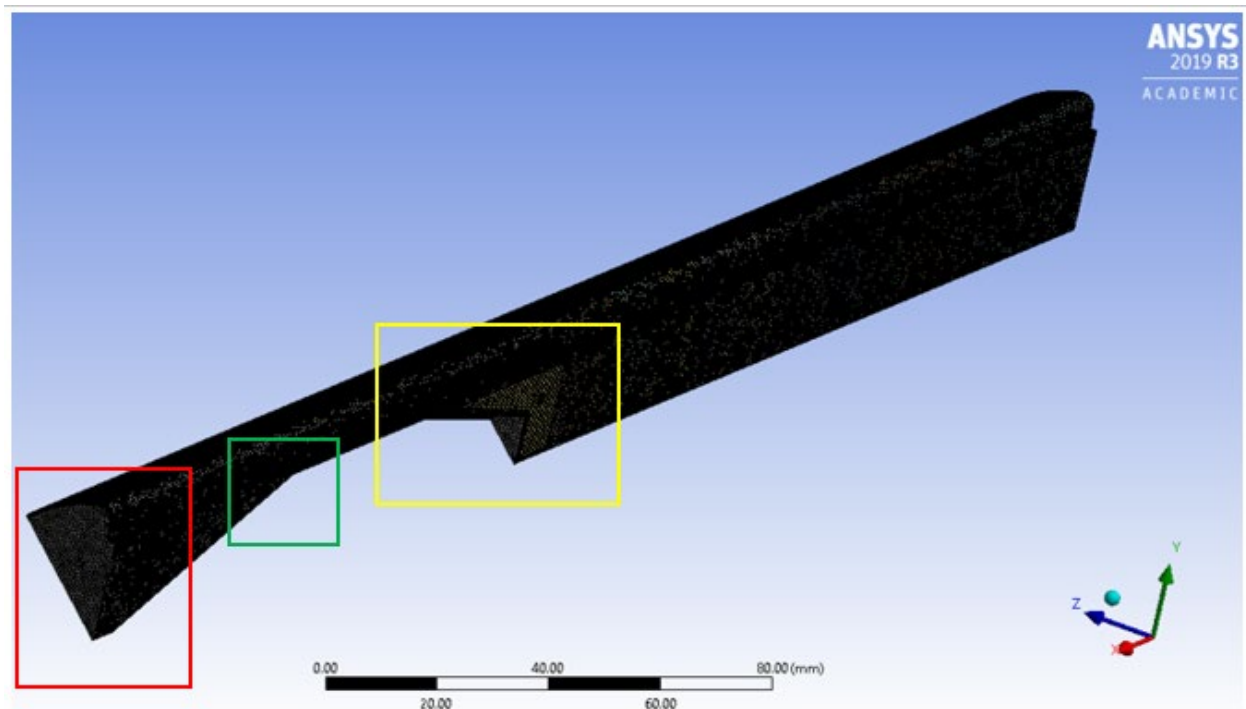


Figure 22 CFD grid of RTRA with ~2.2 million cells regions for detailed grid displays highlighted.

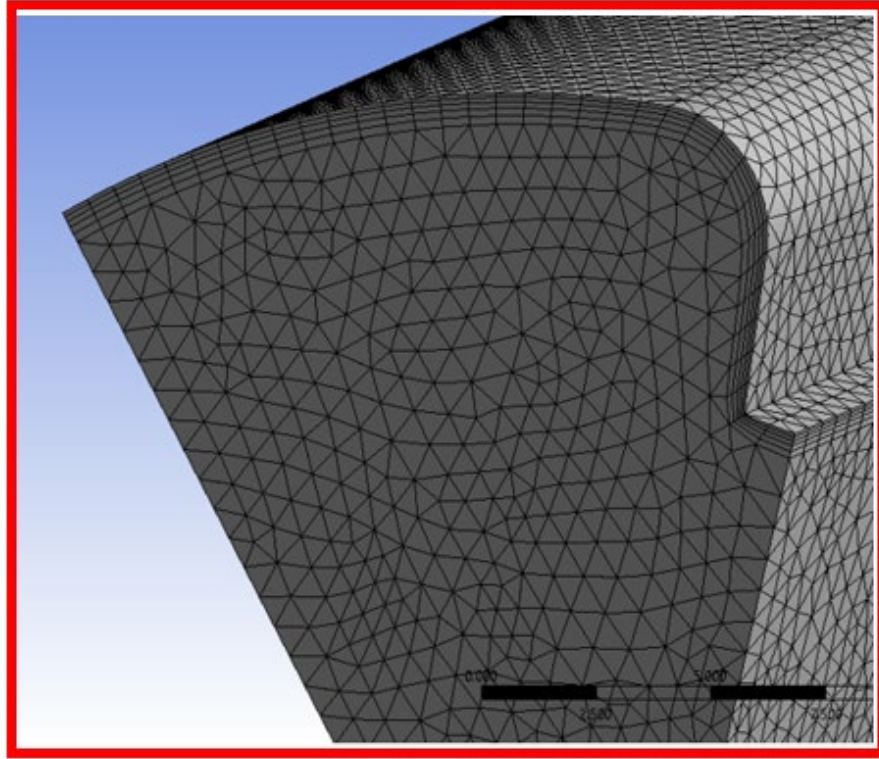


Figure 23 Isotropic grid quality around the inlet and the outlet. A few prism layers were used around viscous surfaces to resolve the boundary layers under the rail and around the walls.

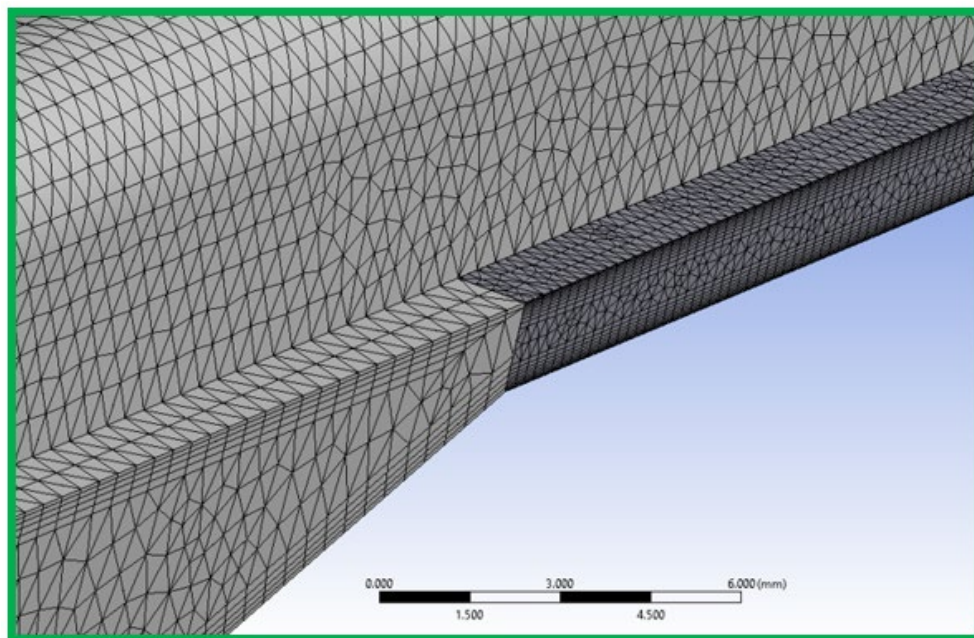


Figure 24 Isotropic grid quality around the projectile and under the rail. Prism layers were used around the projectile surfaces and under the rail to resolve the boundary layers.

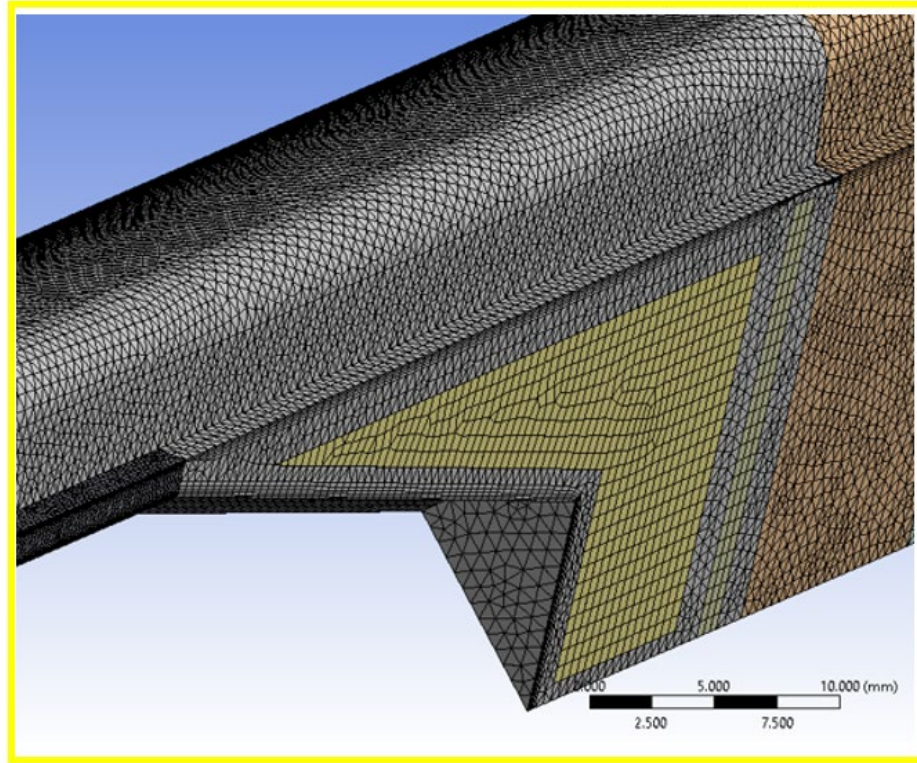
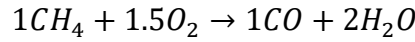


Figure 25 Isotropic grid quality around behind the projectile base, patch, and porous domains.

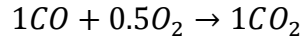
A density-based unsteady Reynolds Averaged Navier-Stokes (URANS) with an implicit-advection upstream splitting method (AUSM) flux solver modeled RTRA operation in a premixed reactive propellant [42]. The spatial discretization was a least-square cell-based gradient with a third order upwind flow, a second order upwind turbulent kinetic energy, and a second order upwind specific dissipation rate. The turbulence model was a 2-equation Shear-Stress Transport (SST) $K-\omega$ viscous in the compressible flow. A species transport model with a volumetric reaction and 2-step methane-air reaction mechanisms were utilized with hybrid finite-rate and eddy-dissipation turbulence-chemistry interaction. The reaction steps are given in Equation 22 and Equation 23. The combustion model in a $1.8\text{CH}_4+2\text{O}_2+7.18\text{N}_2$ mixture with less than 1% mole-fraction of CO, CO_2 and H_2O has an Arrhenius rate relation for the finite-rate chemistry model as

shown in Equation 24 with the coefficients for each reaction listed in Table 1. The pre-exponential factor of Arrhenius rate was increased by five orders of magnitude on both reaction mechanisms to prevent combustion quenching due to numerical dissipation and large temperature drops based on volumetric cell sizes. Lessons learned from the sensitivity study of pre-exponential factor of Arrhenius rate on the combustion characteristics in prior BTRA modeling [44] were used to adjust pre-exponential factors to facilitate RTRA CFD modeling while maintaining reasonable, yet moderate cell counts. The eddy-dissipation rate model [45] [46] parameters for each reaction are shown in Equation 25, Equation 26, and Equation 27 and their coefficients (C_{ED} and D_{ED}) are listed in Table 1 (see Nomenclature for complete description of variables used in Equations 24-27).

Equation 22



Equation 23



Equation 24

$$\sigma_{Arrhenius} = A_{Arrhenius} T^\zeta e^{-\frac{E_a}{RT}} [CH_4]^a [O_2]^b [CO]^c [CO_2]^d [H_2O]^e$$

Equation 25

$$R_{1i,r} = v'_{i,r} M_{w,i} C_{ED} \rho \frac{\varepsilon}{\kappa} \min_\xi \left(\frac{Y_\xi}{v'_{\xi,r} M_{w,\xi}} \right)$$

Equation 26

$$R_{2i,r} = v'_{i,r} M_{w,i} C_{ED} D_{ED} \rho \frac{\varepsilon}{\kappa} \left(\frac{\sum_p Y_p}{\sum_j^n v'_{j,r} M_{w,j}} \right)$$

Equation 27

$$\sigma_{Eddy-Dissipation} = \min(R_{1i,r}, R_{2i,r})$$

Table 1 finite-rate and eddy-dissipation turbulence-chemistry interaction model inputs.

Reaction	$A_{\text{Arrhenius}}$	E_a	ζ	a	b	c	d	e	C_{ED}	D_{ED}
1	5.012e+16	2e+8	0	-0.3	1.3	1	0	1	4	0.5
2	2.239e+17	1.7e+8	0	0	0.25	1	1	0	4	0.5

The CFD domain was initialized with the inlet at 5 atm static pressure and 300 K static temperature. All walls were viscous and adiabatic with the exception of the tail and the base of projectile, which were originally isothermal at 6000 K to initiate combustion. After ignition was established, the tail and projectile base boundaries were reset to be adiabatic walls. The inlet-velocity boundary condition was set to constant 1.2 km/s or 1.4 km/s and the pressure-outlet boundary condition to 0.1 atm static pressure. The viscous tube walls and rails moved at constant velocity or constant acceleration for various CFD simulations while the projectile was stationary in the projectile frame of reference. The patched and porous regions were initialized at 6000 K with 29%CH₄ + 57%O₂ + 14%CO initial mixture mole-fractions. The physical time-step was set to 9e-7 s and 7.71e-7 s for 1.2 km/s and 1.4 km/s simulations, respectively, with 15-20 sub-iterations per time-step. The porous boundary condition changed to the interior-type boundary condition at the 1500th physical time-step after obtaining stable combustion region behind the base of the projectile. These simulations were run 2.0-2.4e+4 time-steps on 30-36 Genuine Intel®-2.00 GHz dual-threaded processors on a high-performance computing server for 2.4e+4 CPU-hours.

Schematics of the front and the side view of an axisymmetric projectile inside of the RTRA are shown in Figure 26. The gap between the shoulder of the projectile and the rail was increased to

provide clarity in this figure, while the actual gap used in the simulation was 0.78 mm. The projectile was segmented to four regions; head/nose-cone, shoulder, tail, and base as shown in Figure 26b. Note that when the projectile moves in the RTRA configuration, it experiences two distinct flow fields. One is due to the interaction between the projectile and the rails (flow near symmetry plane-1 and -3), while the other is due the interaction between the projectile and the tube wall similar to the flow field inside the SBRA (flow near symmetry plane-2 and -4) as shown in Figure 26a. In this report, all flow field quantities were displayed in the symmetry plane-1 with the center of the rail view shown in Figure 26b.

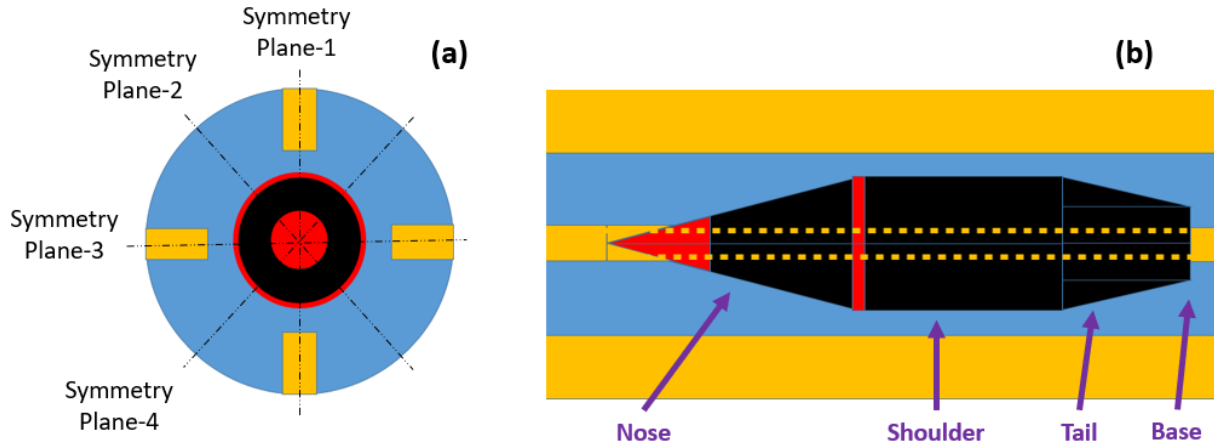


Figure 26 (a) Front view of the projectile in the RTRA configuration. (b) Side view with transparent-dotted rail at 90°.

2.2 CFD Modeling of RTRA at 1.2 km/s and 1.4 km/s

The CFD simulations for 1.2 km/s and 1.4 km/s at 5 atm fill pressure were used to examine the impact of Mach number on the resulting thrust and flow field characteristics. Instantaneous thrust was determined by integrating pressure and shear forces acting on the four projectile segments (nose, shoulder, tail, and base). The corresponding non-dimensional thrust was

calculated by normalizing the instantaneous thrust with the fill pressure and reference bore cross section area. The projectile component thrust breakdown for 1.2 km/s and 1.4 km/s as a function of time are shown in Figure 27a and Figure 27b, respectively. The non-dimensional thrust components associated with nose, shoulder, tail, and base of the projectile are shown with green, magenta, red and blue lines, respectively, and the summation of these four contributions provide the total non-dimensional thrust shown by the black line. Instantaneous flow field pressures (0.1 atm - 70 atm) are shown below the non-dimensional thrust plots after 8 ms and 11 ms of physical flow time in the simulation, which were indicated with purple and red triangles. The 8 ms and 11 ms time marks corresponded to the 9000th and 12000th time-steps ($9\text{e-}7$ s intervals) in the simulation for the 1.2 km/s case in Figure 27a. A shorter time step interval ($7.71\text{e-}7$ s) used in the 1.4 km/s simulation resulted in the completion of 10500th and 14000th time-steps after flow times of 8 ms and 11 ms, respectively (Figure 27b).

For both cases, the thrust contribution from the tail of projectile was larger than that of the base due to its larger projected area, even though the peak pressure at the base was always higher. The net thrust for the 1.2 km/s and 1.4 km/s cases did not reach a steady state over the 11 ms time window of these simulations. The tail thrust component did not reach equilibrium for either velocity, indicating that combustion driven shockwave system had not yet stabilized. This is readily evident in the 1.2 km/s simulation by the forward motion of the combustion wave front in the shoulder region of the projectile in the 3 ms interval shown here (Figure 27a). This process leads to significant heat release in the throat region and eventual unstart. The forward motion of the combustion wave front at 1.4 km/s was very small over the 8 ms to 11 ms interval, even though the tail thrust component varied significantly.

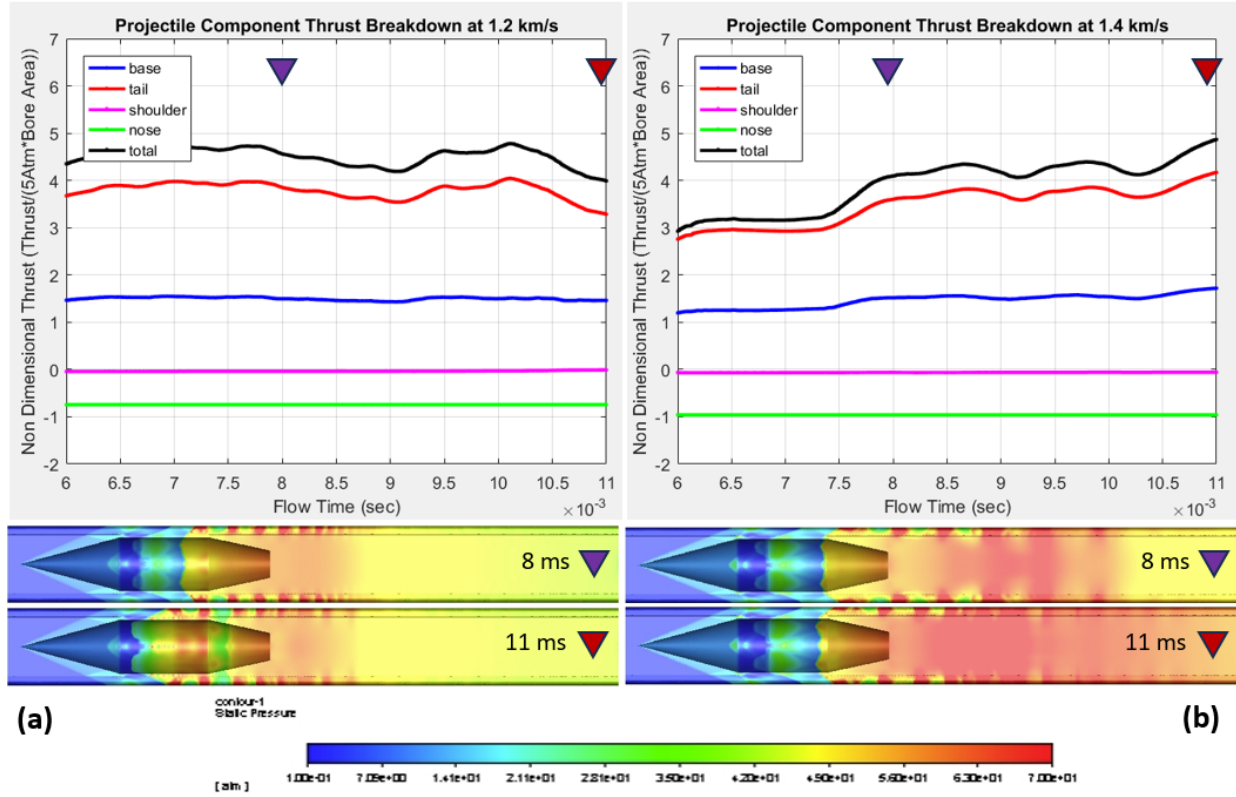


Figure 27 Projectile component non-dimensional forces (nose, shoulder, tail, and base) and static pressure flow field (0.1 atm-70 atm) at 8 ms and 11 ms for (a) 1.2 km/s and (b) 1.4 km/s.

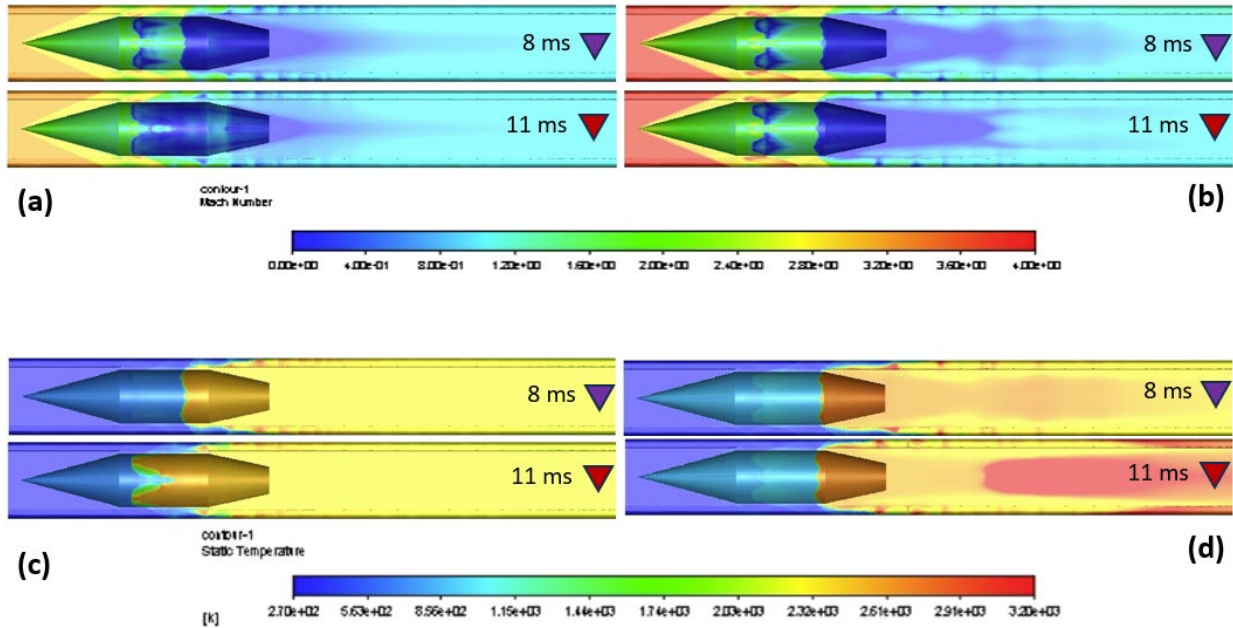


Figure 28 At 8 ms and 11 ms; Mach field (0-4) for (a) 1.2 km/s and (b) 1.4 km/s, Static temperature flow field (270 K - 3200 K) for (c) 1.2 km/s and (d) 1.4 km/s.

Instantaneous flow field Mach number (0 - 4) and static temperature (270 K – 3200 K) are shown in Figure 28a-b and Figure 28c-d, respectively, after 8 ms and 11 ms of physical flow time. The first reflected shock from the tube wall hitting forward section of the shoulder reduced Mach number locally as shown in Figure 28a-b. The flow field between the shoulder and rail was not very sensitive to shockwave impingement and was thus at near sonic velocity throughout its length. The static pressure field at 1.2 km/s had relatively uniform temperature behind the projectile base after 8 ms and 11 ms of physical flow time in the simulation (Figure 28c), whereas static temperature in the core flow behind the base at 1.4 km/s increased during this 3 ms time interval (Figure 28d).

To determine if a stable solution was possible at 1.4 km/s, this simulation was continued for another 11,000 time-steps for a total flow time of ~20 ms. The non-dimensional thrust and flow field pressure at flow times of 14.4 ms and 19.7 ms are shown in Figure 29. After 15 ms, the tail and base thrust components stopped oscillating and settled down to a quasi-steady state condition. The resulting net non-dimensional thrust value of ~4.2 slowly decreased to ~4.0 over the following 5 ms. Even though this simulation indicated that operation of the RTRA was nearly stabilized after sufficient iterations, the continuous forward motion of combustion wave front implies that a steady state solution may not be possible at this velocity. Note that forward motion of combustion wave front was observed for both cases, but such phenomenon occurred at slower rate at 1.4 km/s. Similar transient simulations in SBRA configurations have shown that stable TCRA operation was possible with tapered shoulder projectiles over a relatively wide range of velocities in methane-air propellant [34] [47]. The inability of the current simulations to find a stable operating condition for the RTRA at constant velocity implies that the cylindrical shoulder section

and rail interactions have significant influence on the flow field. These phenomena were examined and are discussed in the next sub-section.

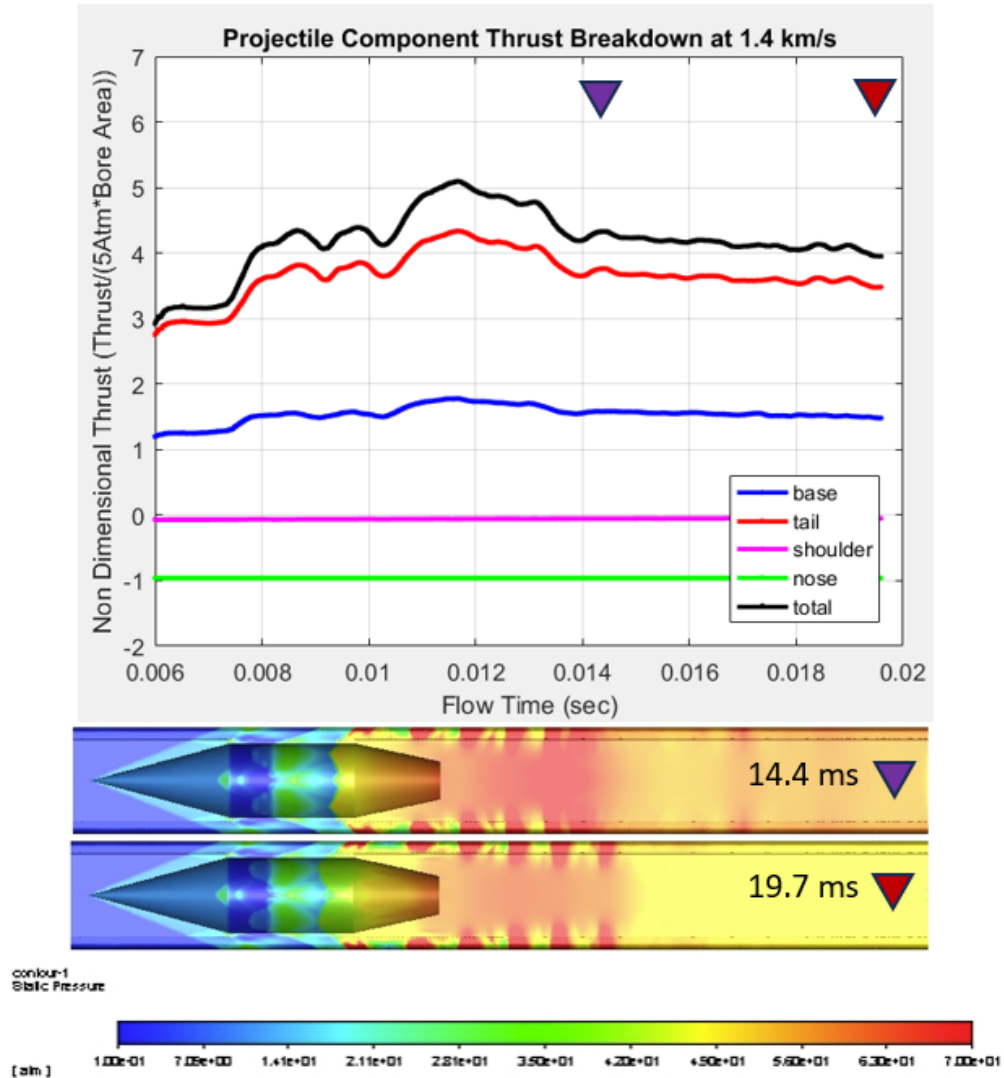


Figure 29 Projectile component non-dimensional forces (nose, shoulder, tail, and base) and static pressure flow field (0.1 atm-70 atm) at 14.4 ms and 19.7 ms for 1.4 km/s.

Straight annular sections used as combustion isolators prevent transient pressure pulses from unstarting air-breathing scramjet engines, however, the fuel is always added downstream and only non-reactive shockwaves are present in the isolator [48]. Conversely, in the RTRA the

propellant flow through the throat region around the projectile shoulder is very reactive. Thus, combustion may be initiated that ultimately thermally chokes the flow in the shoulder region and causes an unstart. The results of these RTRA simulations indicate that indeed this mode of failure may be present when the projectile velocity is constant. The experiments, however, have shown good performance over a relatively wide velocity range. The key difference with the simulations is that the projectiles are always accelerating, thus an effort to model the RTRA with projectile acceleration has been undertaken.

Simulations reported up to this point included a series of CFD simulations that examined the characteristics of RTRA operation at the subdetonative velocities of 1.2 km/s and 1.4 km/s with an axisymmetric projectile. At 1.2 km/s, quasi-steady flow fields were not established in the simulations and the projectile ultimately unstated. Whereas, when the projectile was traveling at 1.4 km/s, its flow field eventually stabilized for a relatively long period of time (~ 5 ms) with a non-dimensional thrust value of ~ 4 . Even though quasi-steady thrust performance was realized, the combustion front wave was slowly moving up and into the shoulder region, which is often a precursor to unstart. Because neither simulation showed stable operation under conditions at which successful experiments were carried out, the influence of projectile acceleration on the performance of the RTRA was then explored as described in the next section.

2.3 CFD Modeling of RTRA at Constant Acceleration

When flow velocity increases in the TCRA, two phenomena occur simultaneously. 1) As velocity increases, the system of shockwave reflections moves aft around the projectile and behind its base, which forces boundary-2/State (2), as shown in Figure 13, to move farther

downstream and increase the length of the combustion zone. 2) Concurrently, higher flow velocities promote stronger turbulent combustion and more rapid heat release rates, which tend to move the thermally choked plane (boundary-2) and combustion wave front forward. If the first phenomenon is stronger than the second one, the thermally choked plane and the combustion wave front continue to move downstream and eventually result in a wave fall-off [9] [10]. If the second phenomenon is stronger than the first one, then the combustion wave front and boundary-2 both move forward initiating a diffuser unstart [9] [10] [26]. The primary effect of acceleration on the quasi-one-dimensional unsteady thrust model is to incur propellant accumulation within the control volume that thereby reduces thrust because of corresponding reductions in the exit flow stream thrust [18].

Effects of acceleration on the flow field and thrust performance of the RTRA were examined using the flow field state at a point in the 1.4 km/s simulation dataset as the initial conditions. The new simulation considered a projectile undergoing constant acceleration at 14.5 km/s^2 ($\sim 1480g$) from 1.4 km/s to 1.5 km/s from 6.5 ms to 13.4 ms. The flow through the diffuser was fully converged at the 6.5 ms point of the simulation, however, the combustion driven shockwave system was not. Nonetheless, the acceleration in the new case was started at around 6.5 ms to assure that the combustion wave front was not initially in the shoulder region. This CFD simulation was then terminated when the projectile velocity reached 1.5 km/s at 13.4 ms. The non-dimensional thrust for the accelerating case was calculated as described in Section 2.2. Instantaneous static-pressure fields extracted at different time steps (shown with inverted triangles) in Figure 30 are compared with the simulations at constant velocity at 1.4 km/s. As flow accelerated to a higher velocity and Mach number, the oblique and reflected shockwaves moved

farther downstream over the projectile shoulder and tail. Note that the non-dimensional thrust for the constant velocity case reached near steady state with an average value of ~ 4.1 after 15 ms (Figure 30a).

During acceleration, the shockwave system on the tail of projectile and combustion zone behind it showed unstable behavior until about the 9.3 ms point of the simulation. Afterwards, the flow field was relatively stable and the non-dimensional thrust of the accelerated case increased slightly before it plateaued to a value of ~ 4.5 after ~ 11 ms (Figure 30b).

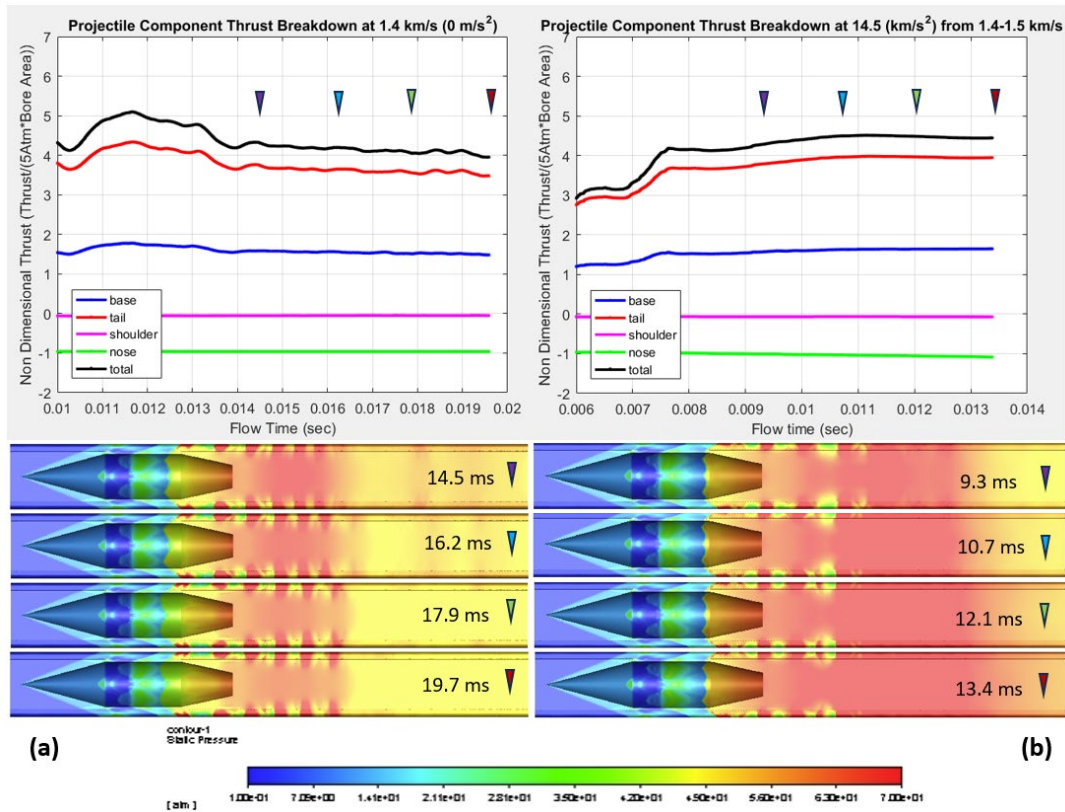


Figure 30 Projectile component non-dimensional forces (nose, shoulder, tail, and base) and static pressure flow field (0.1 atm-70 atm) for accelerations of (a) 0 km/s^2 and (b) 14.5 km/s^2 .

The static pressure profile over the tail and base of the projectile during the time interval from 10.7 ms to 13.4 ms was practically steady. The length of the high-pressure region behind the base,

however, increased over this time interval. This result implied that the expansion of the control volume due to acceleration (phenomenon-1) almost balanced the forward motion of the turbulent combustion region behind the base (phenomenon-2), which resulted in quasi-steady-like performance during that period. The axial pressure fluctuations around the tail and behind the base were stronger under and near the rail walls than those on the tube wall in between the rails (near symmetry plane-1 and -3 and symmetry plane-2 and -4 in Figure 26a, respectively).

Three flow similarities between constant velocity and constant acceleration cases were observed when both cases experienced quasi-steady thrust. 1) The location of combustion wave front remained relatively stationary on the projectile. At constant velocity, the combustion wave front was in the last 30% of the shoulder region during simulations between 15 ms to 19.7 ms. When accelerating, however, the combustion wave front remained stationary at the shoulder-tail conjunction within the time interval between 9.3 ms to 13.4 ms. 2) The respective shockwave patterns remained self-similar over the tail and base for each case through time. Due to increasing Mach number, however, the peak static pressure behind the shockwaves increased in the case with acceleration. 3) The static pressure was radially uniform after the shockwave reflections disappeared a few projectile diameters behind its base. As expected, the static pressure inside the uniform pressure region was less at 0 km/s² than at 14.5 km/s² due primarily to the increase in Mach number. Although, acceleration expanded the high-pressure combustion region farther downstream (phenomenon-1), it also promoted enough turbulent combustion behavior to maintain a relatively high-pressure region behind the base. Thus, the acceleration case yielded nearly the same non-dimensional thrust relative to the constant velocity case when the flow field first became stable at 8 ms (1.42 km/s).

The location and shape of the thermally choked regions behind the projectile for these two cases (0 km/s^2 vs. 14.5 km/s^2) were sought. Instantaneous Mach number fields extracted at various flow times are shown in Figure 31a-b, with the transonic flow region mapped with cyan to light-blue colors. The Mach number contours indicated that the thermally choked region was a 3-dimensional surface a few projectile diameters behind its base, and that a planar 2-dimensional thermally choked region was not ever present. Furthermore, the Mach number at any cross section along axial-direction around the tail and behind the base was lower near the rail walls than on the tube walls (symmetry plane-1 and -3 vs. symmetry plane-2 and -4 in Figure 26a).

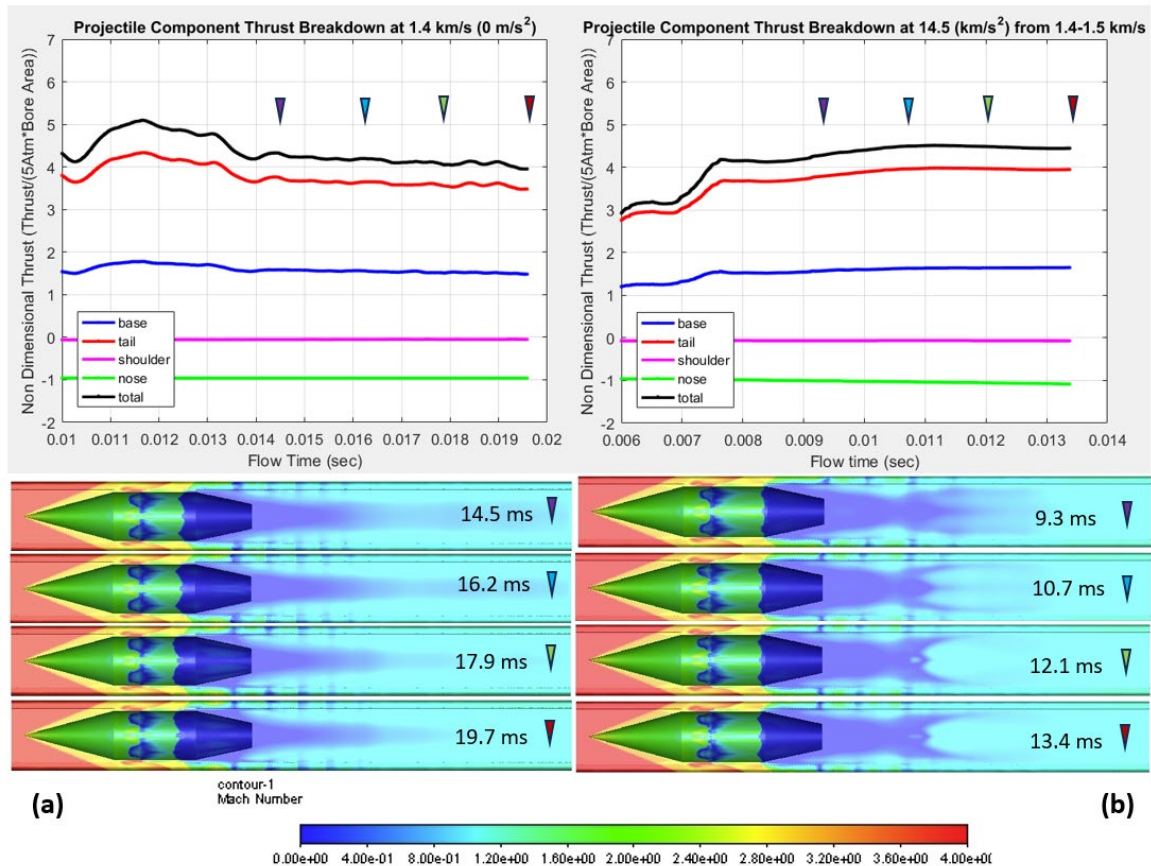
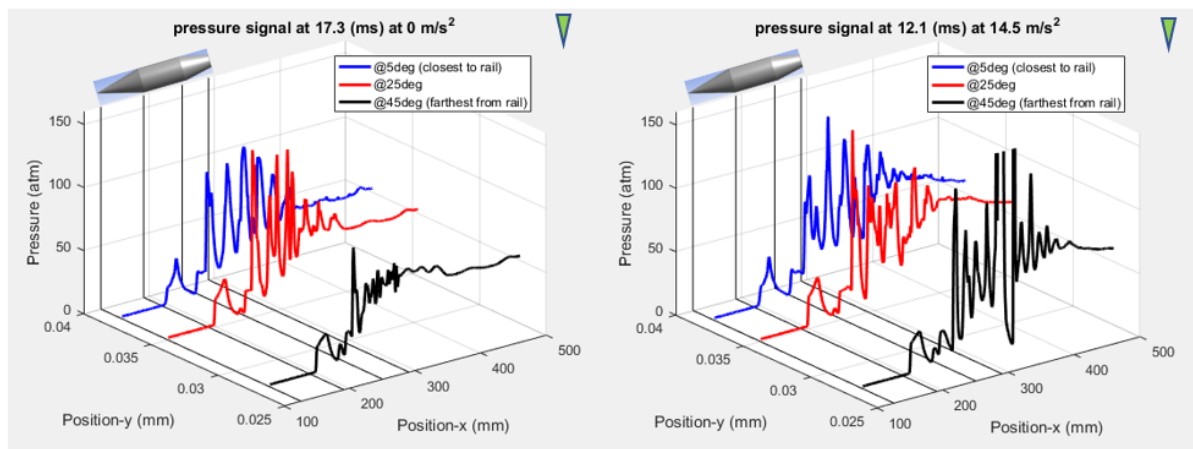
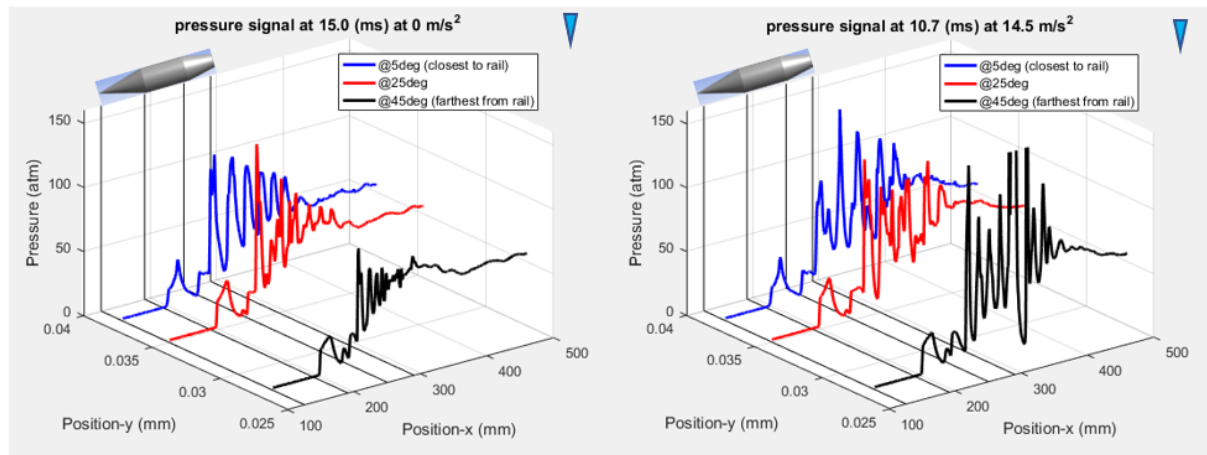
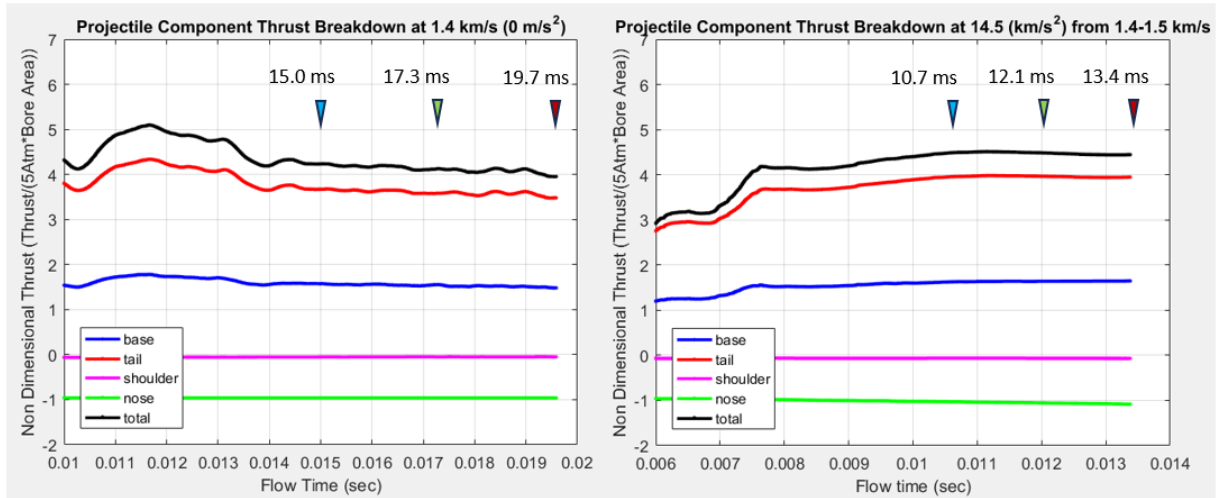


Figure 31 Projectile component non-dimensional forces (nose, shoulder, tail, and base) and Mach number flow field (0-4) from various flow times at (a) 1.4 km/s constant velocity and (b) 14.5 km/s² constant acceleration from 1.4 km/s to 1.5 km/s.

Pressure fluctuations and Mach number variations in the axial-direction around the tail and behind the base near rail and tube walls motivated further investigation of wall pressure profiles at different azimuthal locations as shown in Figure 32. Pressure data on the channel wall from the constant velocity and constant acceleration simulations were extracted from the inlet to the outlet of CFD domains at azimuthal directions of 5° , 25° and 45° relative to the plane symmetry-1 (Figure 32c). In particular, wall pressure profiles along the centerline of the tube walls coincide with experimental RTRA data collected with piezoelectric pressure transducers located in the center of channel in between the rails [39] [43]. Pressure profiles plotted in Figure 32a-b are at the flow times for both cases when their flow fields had stabilized, i.e., at 15 ms, 17.3 ms and 19.7 ms for 0 km/s^2 acceleration and at 10.7 ms, 12.1 ms and 13.4 ms for 14.5 km/s^2 acceleration. In these plots, the locations of the projectile head, shoulder, and tail sections are projected onto the distance-x planes to relate projectile position to tube wall simulation pressure data.



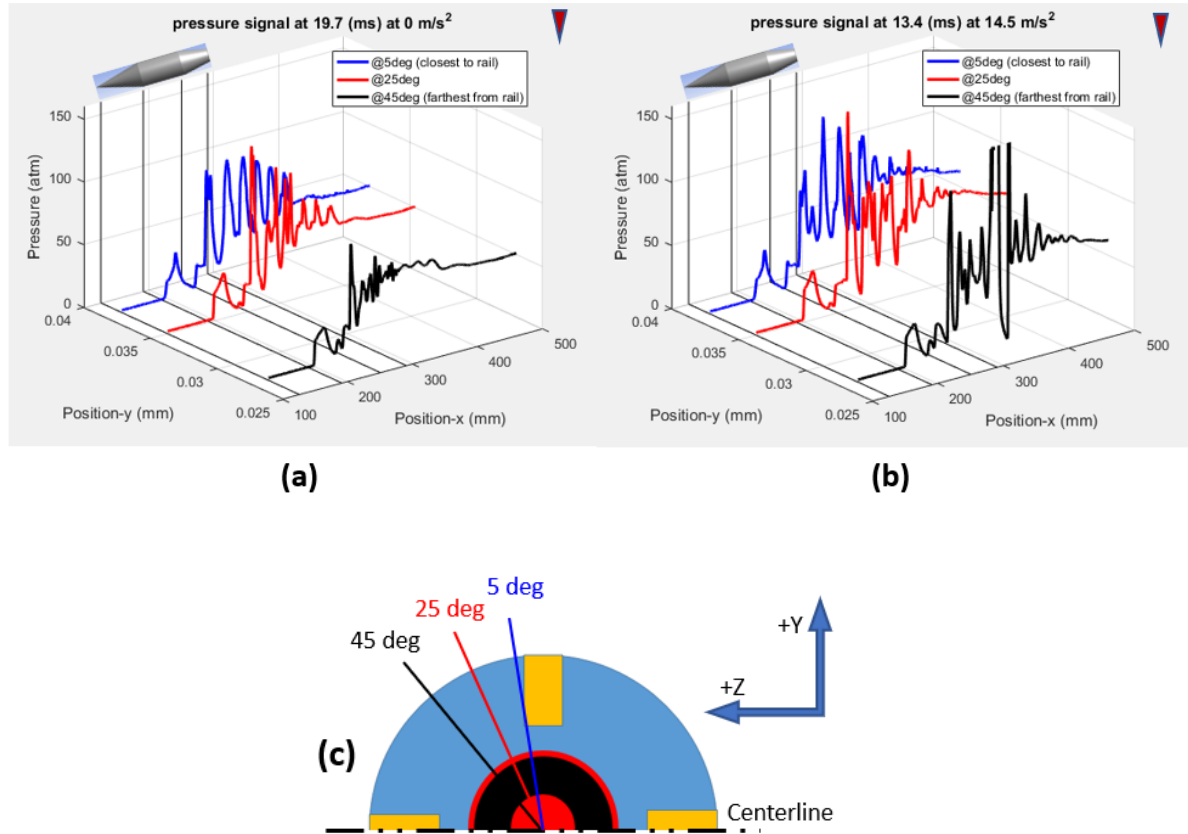


Figure 32 Projectile component non-dimensional forces (nose, shoulder, tail, and base) and wall static pressure data for (a) 0 km/s² at 15 ms, 17.3 ms, 19.7 ms at 0 km/s², (b) 14.5 km/s² at 10.7 ms, 12.1 ms, 13.4 ms at 14.5 km/s², and (c) Forward view of the axisymmetric projectile inside RTRA and azimuthal locations of wall pressure profiles.

In the constant velocity case (Figure 32a), larger pressure amplitude fluctuations were observed near the rail on the channel wall (5° plane) than on the channel wall centerline (45°). The first pressure rise is due to conical shockwave impingement at the wall ahead of the leading edge of the shoulder. The pressure rise behind the lead conical shockwave is sharper and of higher amplitude in both the 5° and 25° planes due to wave interactions with the rails. The strongest shockwave is at the end of the projectile shoulder region, where the supersonic flow undergoes a transition to subsonic. The point where this shockwave contacts the projectile is associated with the combustion wave front. The pressure amplitudes in the combustion zone decreased slightly

as the simulation time was increased. The end of the combustion zone is indicated by the sudden expansion and cessation of oscillatory waves, which is the trademark of a ram accelerator thermal choking point [49]. Thus, the flow is likely thermally choked about two tube diameters (~ 80 mm) behind the projectile base when operating at constant velocity of 1.40 km/s ($M_1 = 3.9$).

In the constant acceleration case (Figure 32b), the pressure traces were from simulations at slightly different velocities (1.45 km/s, 1.48 km/s, and 1.50 km/s). The pressure amplitude fluctuations were larger at the channel wall centerline (45°) than near the rail walls (5°). The shockwave associated with the combustion wave front was near the shoulder-tail junction, and was followed by a series of shockwaves in the combustion zone. The oscillatory behavior changed farther back behind the projectile base (~ 140 mm) than in the constant velocity case, which indicated that the combustion zone had increased in length. In the accelerating cases with the velocity greater than 1.45 km/s, however, the non-dimensional thrust was about 5% greater than in the constant velocity simulation solution at 1.4 km/s.

The comparison between CFD simulations and the experimental data by Legee et. al. [39] [43] showed a good agreement between these datasets. The experimental pressure signal was extracted near 45° plane, even though the projectile velocity was at 1.26 km/s ($M_1 = 3.5$). Good agreement between simulation and experiment pressure fields was found in the conical diffuser region at the nose of the projectile. The experiment also showed strong shockwaves in the shoulder and tail regions of the projectile like those in the simulations. The cessation of oscillatory wave behavior occurs much farther behind the projectile in the experiments (typically 200 mm to 300 mm), but these data were harder to interpret and thus this phenomenon needs to be investigated in more detail. The experimental projectiles were also subject to canting, which can

skew the flow field significantly [50]. More experiments are planned that will use projectiles with longer shoulders to mitigate canting and piezoelectric transducers at different azimuthal locations for higher resolution pressure field measurements.

In summary, a CFD simulation was carried out for an axisymmetric projectile while it was undergoing constant acceleration at 14.5 km/s^2 from 1.40 km/s to 1.50 km/s . This simulation showed that acceleration was able to stabilize the flow field in a shorter amount of time than the transient period of the constant velocity simulation. The combustion wave front, however, moved slowly forward into the projectile shoulder region as velocity increased, which indicated that an unstart was likely to eventually arise. Nonetheless, the success of the simulations to show favorable influence of acceleration on the flow field indicates that projectile acceleration is a stabilizing factor for RTRA operation.

Flow field details were examined to determine the influence of rails on the shockwave system and the nature of the thermally choked region behind the projectile. The rail influence on the flow field of the accelerating projectile was to dampen the shockwave reflections near the rail when compared with those in the center of the channel. The experiments and simulations showed a strong shockwave at the end of the projectile shoulder that corresponded to the combustion wave front. Strong shockwave oscillations persisted for several projectile diameters behind its base. The sonic Mach number in the simulations was a 3-D surface stretching rearward behind the projectile. In both experiments and simulations, this corresponded to the cessation of significant pressure pulsations downstream of the combustion zone.

2.4 CFD Modeling of RTRA with Projectile Modifications at 1.4 km/s

Additional simulations of four different projectiles moving at constant velocity (1.4 km/s) in a RTRA were used to determine if various tail cone shape modifications would suppress or promote the forward motion of the combustion wave front under conditions where it was seen to move forward on the baseline projectile. The section side views of these projectiles are shown in Figure 33. All five projectiles had the same shoulder and base diameter, as indicated with yellow and green arrows. In addition, all projectiles had the same 12° tail taper as shown with yellow dashed lines. The three tail cone designs involving serrations/chevrons as shown in Figure 33b-d. The Baseline projectile configuration is shown in Figure 33a, and a version with its shoulder extended to the same length as those with a shoulder chevron (Figure 33b and Figure 33d) is shown in Figure 33e.

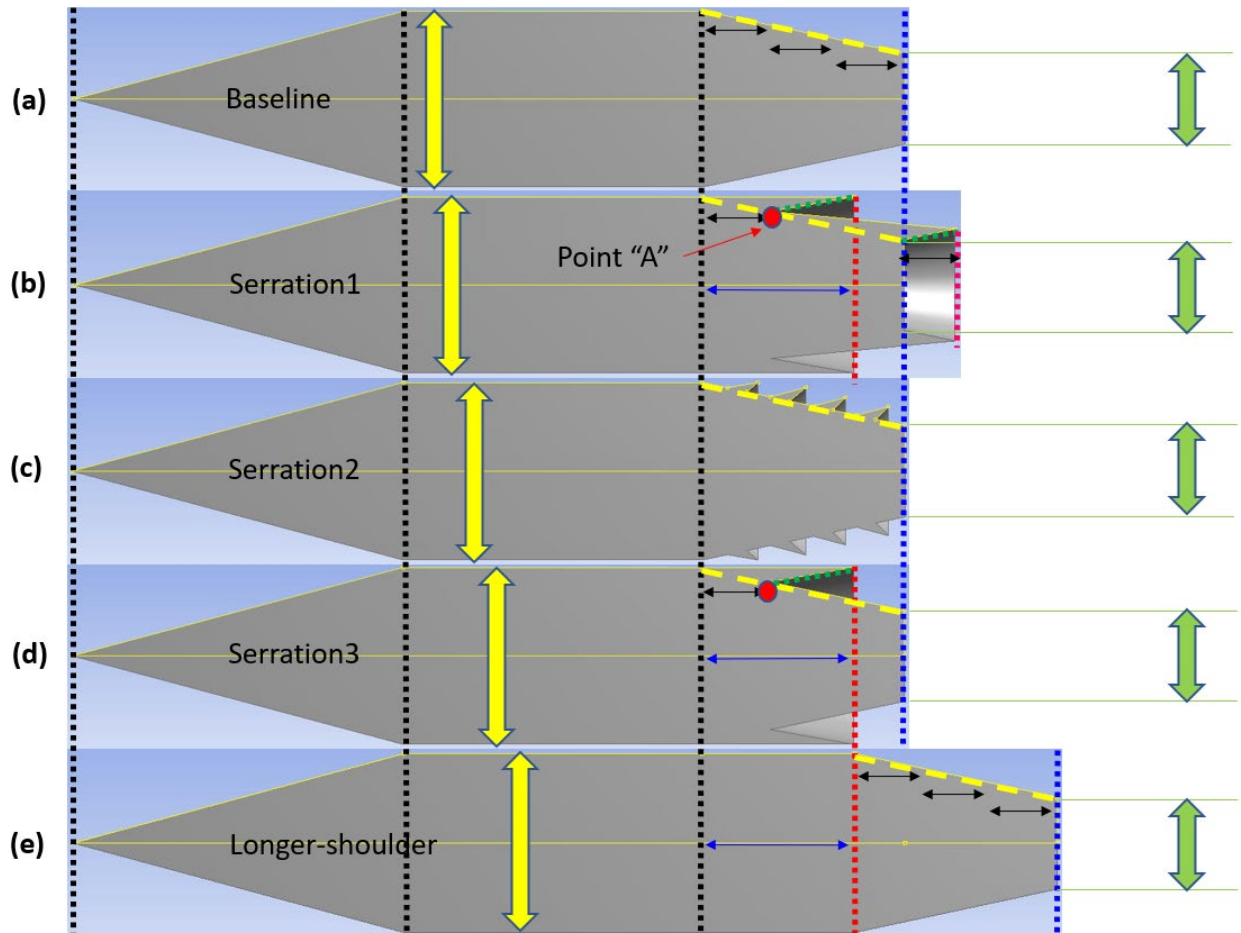


Figure 33 Section views of axisymmetric projectile configurations studied in RTRA operation at constant velocity of 1.4 km/s.

Serration1-projectile had two serrations or chevron features over its shoulder and base with recesses having an upward slope 13° , indicated with green dotted line in Figure 33b. The serration at the shoulder diameter extended the annular shoulder region to the red dotted line. The intersection of the green dotted line with yellow dashed line at point "A" was at approximately 1/3rd of length of the baseline tail, as indicated with the black arrows. The base of Serration1-projectile was also extended by 1/3rd of length of the baseline tail to the dotted magenta line shown in Figure 33b. Serration3-projectile, shown (Figure 33d), was identical to Serration1-projectile at its shoulder region; while its base was identical to the baseline projectile. The

Serration2-projectile (Figure 33c) had four serration features over its tail that protruded upward and had recess cavities. The longer-shoulder projectile (Figure 33e) was included in this study to distinguish the effects of increasing the shoulder region length from the influences of a recessed cavity that terminated on the tail cone.

The non-dimensional thrust from simulations at a constant velocity of 1.4 km/s for the Baseline, Serration1 and Serration2 projectiles are shown in Figure 34a-c. The flow field evolution differed for each projectile during the transient period after the removal of the porous boundary used to facilitate ignition, as shown by static-pressure maps for these three projectiles at the simulation times indicated with inverted triangles. Ultimately, however, quasi-steady thrust conditions were established within approximately 15 ms of simulation flow time. The most rapid establishment of a quasi-steady flow field for these simulations occurred within ~12 ms for the Serration1 configuration. The quasi-steady non-dimensional thrusts for the Baseline, Serration1 and Serration2 simulations were approximately 4.2, 3.6, and 2.8, respectively. The low thrust for Serration2 case is due in part to increased total pressure losses over the tail serrations and in the combustion zone behind the projectile, manifested by the low static pressures in these regions as shown in Figure 34c.

The significant thrust variations of these simulations indicated that tail features significantly influenced the operating characteristics of the projectiles. Furthermore, both the Serration1 and Serration2 projectiles had the combustion wave front on the rear of the shoulder region, and thus were expected to unstart before the Baseline projectile if the simulations were continued for a long enough time. Nonetheless, the rapid establishment of quasi-steady flow in the Serration1 projectile encouraged the exploration of similar configurations.

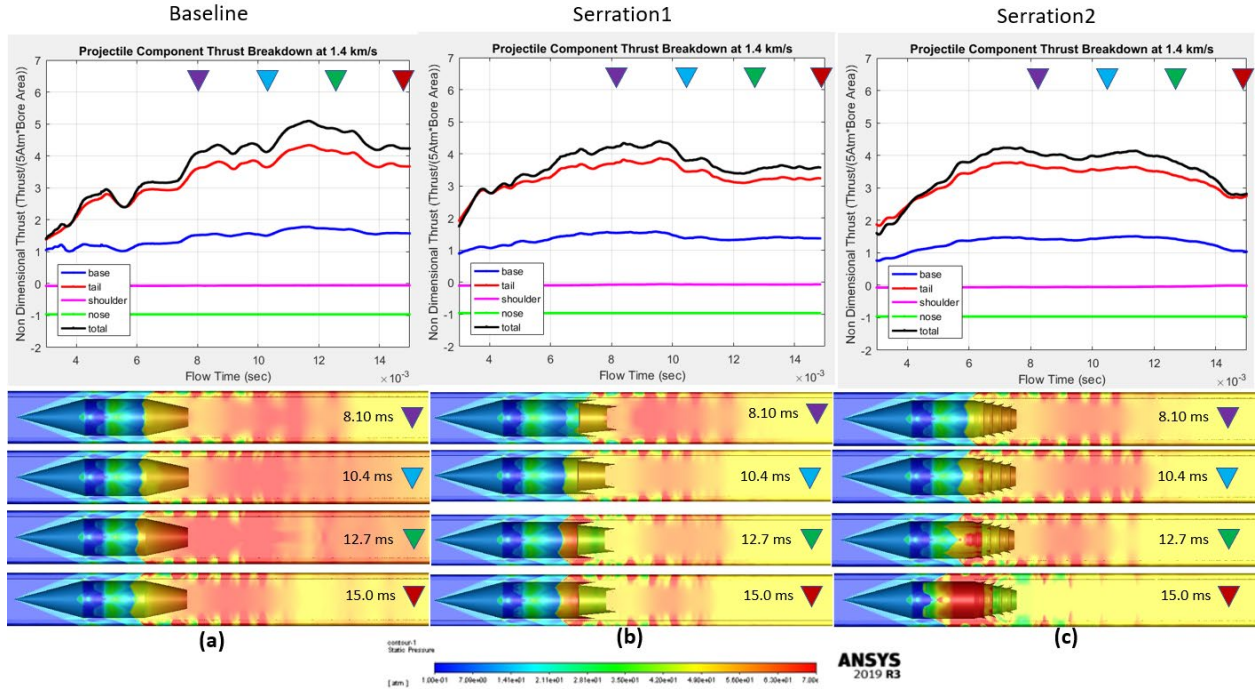


Figure 34 Projectile component non-dimensional forces (nose, shoulder, tail, and base) and static-pressure flow field (0.1 atm-70 atm) at 1.4 km/s for (a) Baseline, (b) Serration1 and (c) Serration2.

The impact of altering shockwave reflection patterns versus promoting or suppressing turbulent combustion due to the serration features had to be decoupled. As a result, the Serration3 configuration (Figure 33d) was generated to examine the effects of the serration extension feature to the shoulder of projectile when it had a bluff base. The Serration3 shoulder feature was the same as in Serration1 (Figure 33b) while its base was the same as that of the Baseline projectile. Simulations of the Serration3 case stabilized the flow field even more quickly than the Serration1 case, as shown in Figure 35b. The static pressure field data for Serration3 case indicate that the combustion region remained a few projectile diameters behind its based during the transient phase of the simulation.

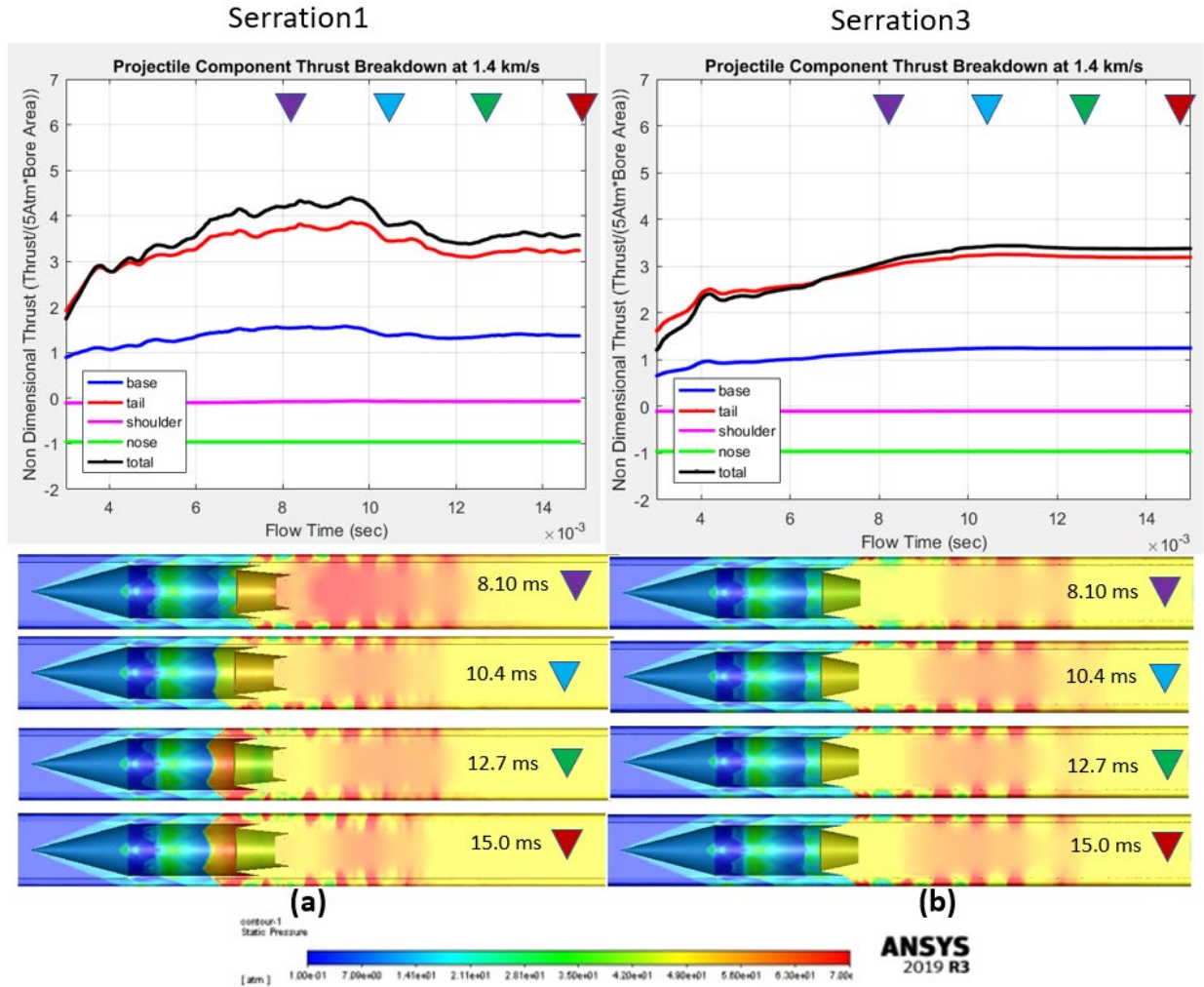


Figure 35 Projectile component non-dimensional forces (nose, shoulder, tail, and base) and static-pressure flow field (0.1 atm-70 atm) at 1.4 km/s for (a) Serration1 and (b) Serration3.

At the end of the simulation (15 ms), the combustion wave front was attached to the serration on the shoulder and did not protrude into the throat region. The maximum static pressure for Serration3 case was found to be lower than that of Serration1. These characteristics of Serration3 case indicate that a quasi-steady flow field can be established without any sign of unstart behavior; however, its non-dimensional thrust is $\sim 5\%$ and $\sim 19\%$ lower than that of Serration1 and Baseline cases, respectively.

Note that the serration feature that extends the shoulder of projectile also generates a strong shear layer as flow separates over that feature. Chemical reactions happen inside the shear layers as they expand from the tip of the serration feature on the shoulder toward tube walls. Although not shown here, the expansion of the shear layer toward tube walls and downstream of the base cause chemical reactions and heat release to move away from the tail and base of the projectile and leads to a smaller pressure increase behind the base. This behavior is the likely cause of the lower pressure amplitude in the Serration3 case.

To decouple the influence of longer shoulder length, which has more reflected shockwaves in the shoulder region, from the expansion of shear layers over the shoulder serration on thrust performance, a longer shoulder projectile configuration was generated (Figure 33e). This projectile had a shoulder length equal to that of the Serration1 and Serration3 configurations, but it was longer in its overall length. Simulation results with the longer-shoulder projectile were not successful in establishing a quasi-steady flow field, as shown by the static pressure flow field maps in Figure 36b. The combustion wave front appeared at the end of the shoulder region early in the simulation and propagated forward up to the point of incipient unstart after 10.4 ms. Thus, the serration recess at the end of the shoulder had a significant role in stabilizing the flow field. The longer-shoulder simulation result does not bode well for applications where long projectiles are to be accelerated in the RTRA, however, the addition of a shoulder extension with a recess as in the Serration3 configuration may prove to be quite useful. The longer-shoulder and Serration3 projectile configurations will be explored in upcoming RTRA experiments.

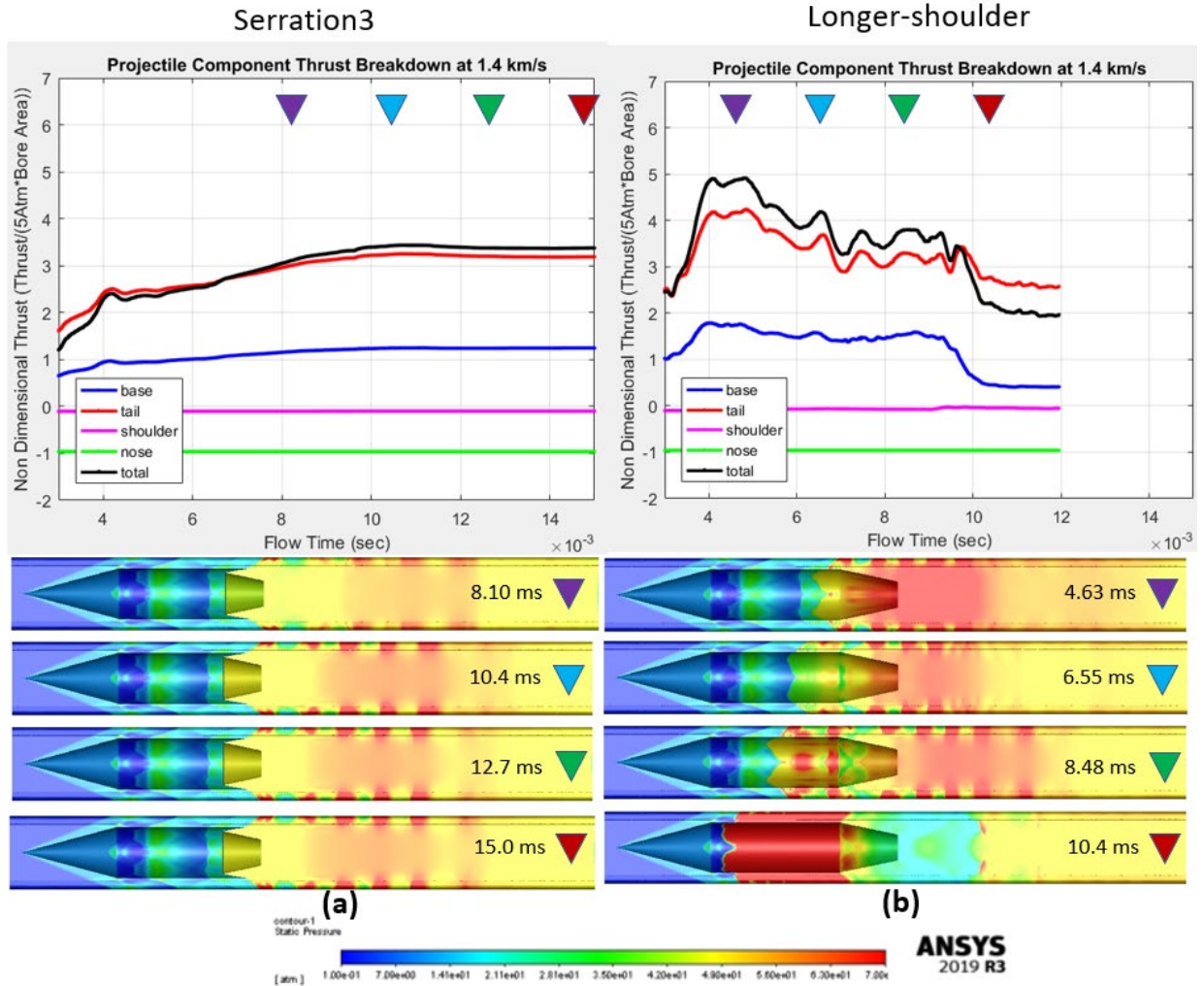


Figure 36 Projectile component non-dimensional forces (nose, shoulder, tail, and base) and static-pressure flow field (0.1 atm-70 atm) at 1.4 km/s for (a) Serration3 and (b) Longer-shoulder.

In summary, an investigation of projectile geometry effects on RTRA operation via CFD simulations at constant velocity (1.4 km/s) found that multiple serration features on the tail promoted vigorous combustion that inhibited the stabilization of the pressure field, leading to early unstart compared to the Baseline projectile. Whereas when using a flat-tailed projectile, extending the shoulder length with a recessed serration at the shoulder suppressed the forward moving combustion process and stabilized the flow field. Lastly, extending the shoulder length

while using a flat tail promoted the forward motion of the combustion wave front and resulted in an early unstart. Thus, the CFD simulations were able to identify useful projectile geometry modifications that stabilizes the flow field and suppresses unstart such as the recessed serration feature at the shoulder. Experiments to investigate the influence of the more promising geometric features are planned.

3. CFD Modeling of Baffled Tube Ram Accelerator in Reactive Flow

To date, operation at velocities up to 2.7 km/s have been demonstrated in the SBRA and up to 1.4 km/s in the BTRA. Note, neither of these peak velocities are near the limits of operation considered to be engineering feasible. The SBRA has significant potential to be able to accelerate projectiles up to ~6 km/s, whereas the BTRA can be started at much lower velocities than possible with the SBRA while operating with substantially higher thrust at a given fill pressure up to its theoretical limit of ~3 km/s. Thus, an optimized ram accelerator launch system may utilize BTRA stages at the beginning of the tube and transition into SBRA in later stages to achieve maximum velocity. The BTRA can operate at lower velocity in a more energetic propellant mixture to achieve higher thrust without changing the operating fill pressure, then the projectile can transition to the SBRA. However, there is a projectile incompatibility between these two ram accelerator configurations. The SBRA requires finned-projectiles while the BTRA requires axisymmetric projectiles. To solve this problem, an axisymmetric projectile can, in principle, be accelerated in a BTRA and then make a transition to a RTRA at the velocity where the latter is more effective at accelerating the projectile at a given fill pressure. Key to optimizing this application is understanding the operation of the BTRA over a wide range of Mach numbers for various

projectile and baffle geometry variations. The status of the ongoing CFD study is presented in this Chapter.

3.1 Development and Implementation of BTRA CFD Model

Transient CFD modeling of the RTRA carried out in a $1/8^{\text{th}}$ symmetry computational domain accounted for the presence of rails and an axisymmetric projectile with ANSYS Fluent software [42]. The RTRA CFD was modeled in the projectile frame of reference where the propellant flow, surrounding walls, and rails moved at constant velocity and/or constant acceleration relative to the projectile. Simulations of the BTRA, however, must be carried out in the laboratory frame of reference because of the projectile-baffle interactions. Also, if BTRA is modeled in the projectile frame of reference and flow move supersonically over the projectile, the shockwave interaction between baffle walls appear ahead on the projectile presence. A section view of an axisymmetric projectile traveling in a rail-less BTRA configuration is shown in Figure 37. Within the CFD domain of the BTRA configuration, the projectile must move at supersonic velocity between baffles where shock waves interact with the projectile and surrounding walls and unsteady turbulent combustion phenomena follow the projectile on the body and/or behind its base.

Note that the CFD domain of BTRA configuration studied in this chapter were designed such that the projectile moved from left to right as a function of time. It was more convenient to observe flow field phenomena as a function of time and compare them against the non-dimensional thrust as a function of time plots where the projectile moved from left to right inside the stationary BTRA configurations.

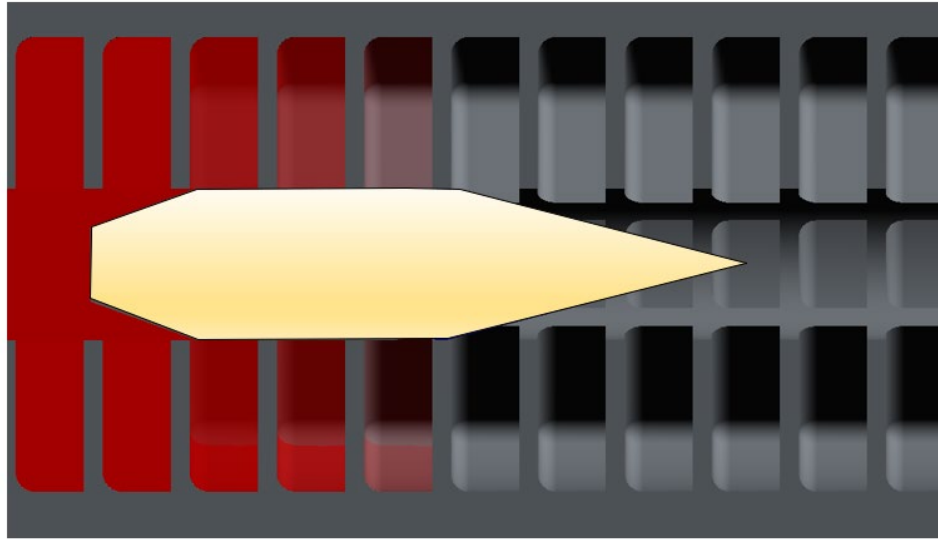


Figure 37 An axisymmetric projectile and BTRA geometric parameters.

The CFD model of the BTRA was created using *Dynamic-Mesh-Layering* [51] and *User-Defined-Function* (UDF) [52] capabilities of ANSYS Fluent to generate simulations in the laboratory frame of reference. Results reported here used axisymmetric calculations.

The computational model of the BTRA has multiple domains with significantly different characteristics relative to each other. The projectile is surrounded by a rigid domain which moves with the projectile at constant velocity and/or constant acceleration. Initially, there is a rigid patch domain around the tail and base that moves with the projectile to ignite the propellant mixture. Furthermore, a rigid porous domain with high flow resistance characteristics placed behind the patch domain stabilizes combustion on the tail and the projectile base before it is removed; i.e., the porous boundary condition is changed to the “interior” boundary condition after a few hundred time-steps after the simulation begins. The porous domain facilitates establishing a high pressure and high temperature region behind the base of the projectile in a manner analogous to using a tube obturating piston for starting the ram accelerator [26]. The purpose of rigid

domains is to provide a uniform cell size domain around the projectile for the flow field to develop as it passes through the baffles.

There are two deforming domains ahead and behind the projectile which are attached to the rigid domains around the projectile as shown in Figure 38. The downstream deforming domain contains structured grid/cells that are stretched and then split during the simulation while the upstream deforming domain cells are compressed and then collapsed as the rigid domains move with the projectile. The fluid domains located within the baffled chambers, above the moving deforming and rigid projectile domains, remain stationary in the laboratory frame of reference. There are two stationary ignition/patch domains inside each of the first nine baffle chambers of the simulation to facilitate the ignition process as the projectile impulsively starts moving at the desired velocity. An UDF is used to assign a constant velocity and/or acceleration to the projectile, rigid domains, and to the corresponding boundaries that are subjected to stretching or compressing.

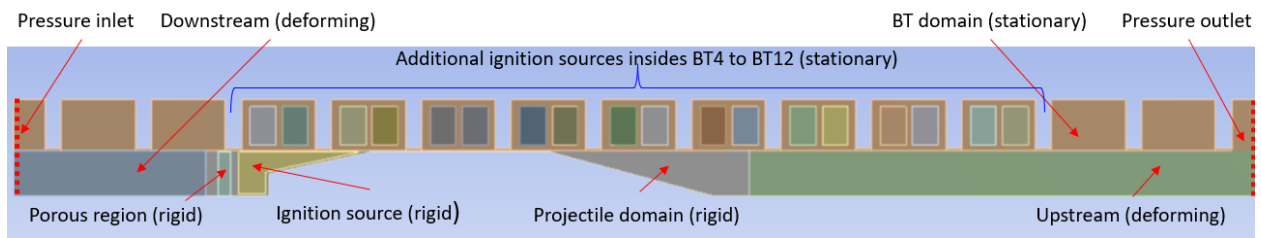


Figure 38 Two-dimensional CFD domains of an axisymmetric projectile inside the BTRA configuration.

The CFD domain initially consists of about ~300,000 cells/grids with isotropic unstructured grids around the projectile and inside the baffled chambers with a maximum cell size of 0.5 mm. Since the collapse and split factors of deforming domains are not equal, more cells are generated due to stretching and split factor inside the downstream domain that increases the total cell

counts (~600,000 cells/grids) when the projectile domain gets closer to the pressure outlet boundary toward the end of the simulation. The isotropic characteristic of the CFD domain provided an unbiased opportunity to establish combustion around the projectile and propagate in any direction as necessary. The BTRA CFD domain originally had 52 baffled tube chambers, but it was further extended to 70 baffle chambers with the flow field data being collected from baffle 15th to 70th after the propellant ignition transients have died away. The entire CFD domain of BTRA is shown in Figure 39.

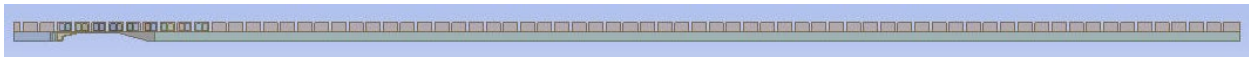


Figure 39 2-dimensional axisymmetric CFD domains of BTRA with 70 baffle chambers.

The boundary layers on the no-slip walls of the projectile are resolved with up to 6 layers of quadrilateral cells whose height grew smoothly by a rate of 1.2 from the first cell with a height of about 0.1 mm. The quadrilateral structured cells inside deforming regions initially has a cell height of 1.2 mm. Multiple layers of quadrilateral structured cells (8-10) at 0.1 mm maximum height is used between the projectile shoulder and the baffle bore, i.e., minimum gap clearance between the projectile body and the baffled tube bore, to capture flow field dynamics at minimum gap regions.

The BTRA grids around the projectile, inside baffle chambers, and inside deforming upstream and downstream are shown in Figure 40. Grid details in minimum gap region and around the projectile nose and shoulder shown in Figure 41 are from inside the region indicated by red box in Figure 40. Cells were concentrated around the baffle ends to better resolve these regions of the flow field and to stabilize the calculations. Note that the rectangular cells inflated to capture

boundary layer behavior were only applied to the projectile because there was very little relative flow motion next to the walls within the baffle chambers.

The Fluent Solver setup and equations describing the chemical reactions of turbulent combustion in BTRA are identical to those described in Section 2 (2.1 Development and Implementation of CFD Model for RTRA Operation) for the RTRA and are repeated in this section for completeness. In the next section, 3.2 CFD Modeling of BTRA Using Methane-Air Multi Reactions Mechanism Chemistry, a brief description is provided about what methane-air multi reaction mechanism chemistry modeling of BTRA was explored.

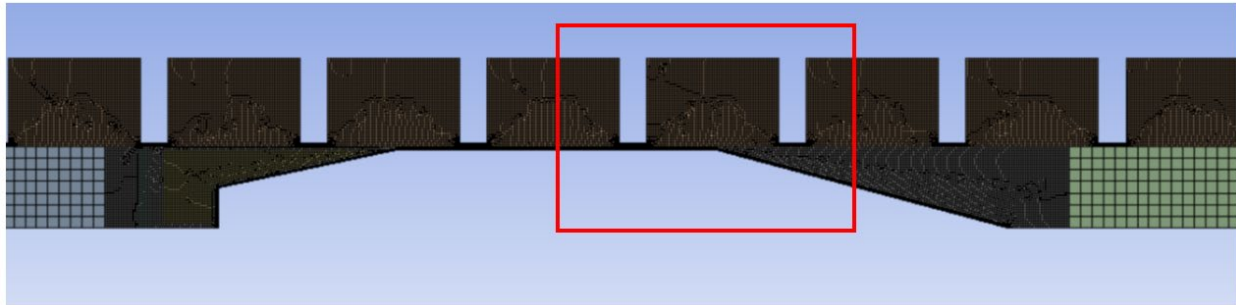


Figure 40 Unstructured grid around the projectile and inside the baffle chambers (rigid and stationary domains) with structured grid ahead and behind the projectile (deforming domains). The detail inside the red box is shown in Figure 41.

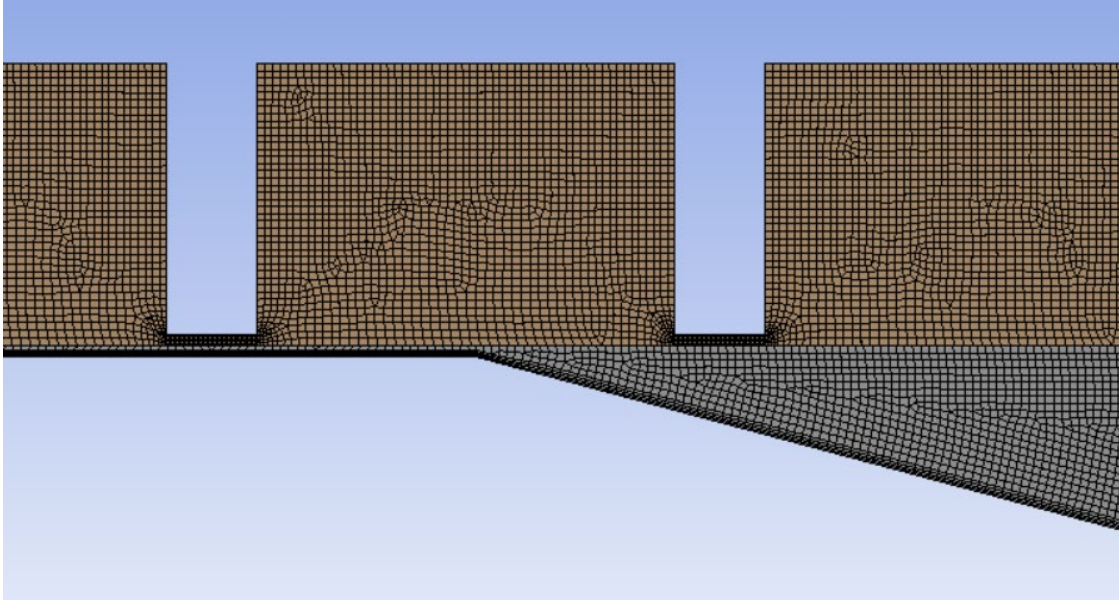


Figure 41 Cell/grid distributions at minimum gap region and around the projectile body.

A density-based unsteady Reynolds Averaged Navier-Stokes (URANS) with an implicit-advection upstream splitting method (AUSM) flux solver simulated the BTRA in a premixed reactive flow [42]. The spatial discretization was a least-square cell-based gradient with a third order upwind flow, a second order upwind turbulent kinetic energy, and a second order upwind specific dissipation rate. The turbulence model was a two-equation Shear-Stress Transport (SST) K- ω viscous in the compressible flow. A species transport model with a volumetric reaction and two-step methane-air reaction mechanisms were utilized with hybrid finite-rate and eddy-dissipation turbulence-chemistry interaction. The reaction steps are given in Equation 22 and Equation 23 (Section 2.1). The combustion model in a $1\text{CH}_4+2\text{O}_2+4.67\text{N}_2$ mixture with less than 1% mole-fraction of CO , CO_2 and H_2O has an Arrhenius rate relation for the finite-rate chemistry model described in Section 2.1. The pre-exponential factor of Arrhenius rate was increased by five orders of magnitude on both reaction mechanisms to prevent combustion quenching due to

numerical dissipation and large temperature drops based on volumetric cell sizes. Lessons learned from the sensitivity study of pre-exponential factor of Arrhenius rate on the combustion characteristics in prior BTRA modeling [44] were used to adjust pre-exponential factors to facilitate BTRA CFD modeling while maintaining a reasonable/moderate cell counts. The eddy-dissipation rate model [45] [46] parameters for each reaction are shown in Equation 25, Equation 26, and Equation 27 (Section 2.1) and their coefficients are listed in Table 1 finite-rate and eddy-dissipation turbulence-chemistry interaction model inputs. See Nomenclature for complete description of variables used in Equation 24, Equation 25, Equation 26, and Equation 27.

The CFD domain was initialized with a pressure inlet and pressure outlet at 20.4 atm static fill pressure (300 psig) and 300 K static fill temperature with 5% turbulent intensity and turbulent viscosity ratio at 10. All walls were viscous and adiabatic with the exception of the tail and the base of projectile, which were originally isothermal at 6000 K to initiate combustion. After ignition was established, the tail and the base boundaries were reset to be adiabatic walls.

An UDF was used to move the projectile domain, ignition/patch region around its tail, and the porous domain at constant velocities, e.g., 1.0, 1.1, 1.2, or 1.4 km/s, or starting with 1.0 km/s and then accelerated to higher velocities. The constant acceleration cases were; 1) $\sim 78.5 \text{ km/s}^2$ ($8000g \text{ m/s}^2$) from 1.0 to 1.1 km/s or, 2) $\sim 192 \text{ km/s}^2$ ($19656g \text{ m/s}^2$) from 1.0 to 1.2 km/s over 40-45 baffles span in latter part of the simulation. The ignition/patch region around the tail-base, porous domain, and stationary ignition/patch regions inside first few baffle chambers were initialized as shown in Figure 42; 1) The porous domain was initialized to 7000 K and 68 atm (1000 psi) with $30\% \text{CO}_2 + 60\% \text{H}_2\text{O} + 10\% \text{CO}$ initial mixture mole-fractions by volume at the beginning of simulation (t_0), 2) The ignition/patch domain around the projectile was initialized to 7000 K and

68 atm (1000 psi) with 30%CO₂ + 60%H₂O + 10%CO initial mixture mole-fractions by volume at t_0 , 3) The stationary ignition/patch (Type-I shown in red boxes in Figure 42) inside baffle chamber was initialized to 600 K and 20.4 atm (300 psi) with 33%CH₄ + 66%O₂ initial mixture mole-fractions by volume at t_0 , and 4) The stationary ignition/patch (Type-II shown in blue boxes in Figure 42) inside baffle chamber was initialized to 600 K and 20.4 atm (300 psi) with 30%CO₂ + 60%H₂O + 10%CO initial mixture mole-fractions by volume at t_0 .

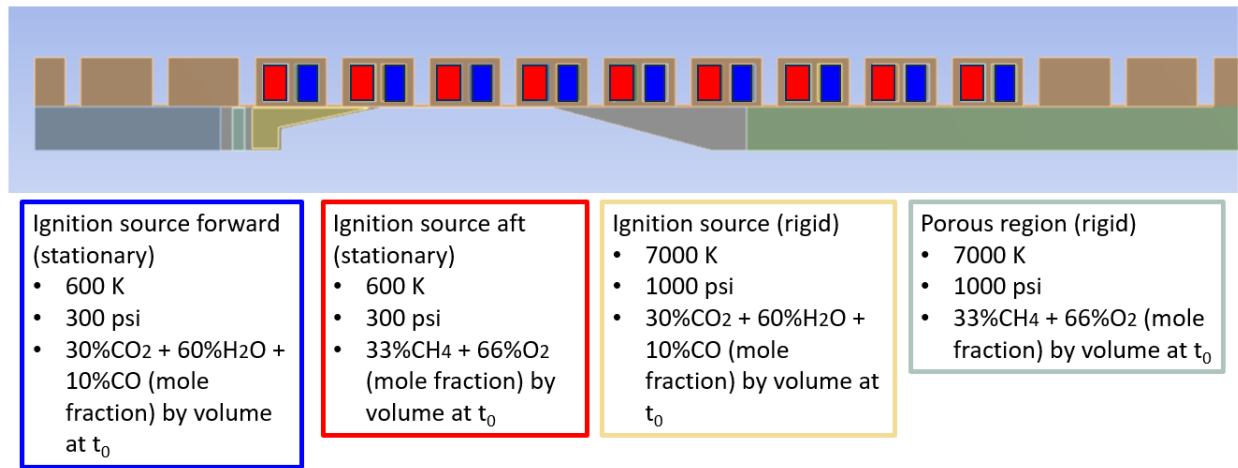


Figure 42 Ignition and porous domain initial conditions.

The physical time-step varied for different simulations ranging from 3.5e-8 to 5.0e-8 seconds with 35-28 sub-iterations per time-step. The porous boundary condition changed to the interior-type boundary condition around 1250th physical time-step after obtaining stable combustion region behind the base of projectile. These simulations were run 4.3e+4 to 4.6e+4 time-steps on 37 Genuine Intel®-2.00 GHz dual-threaded processors on a high-performance computing server for 1.9e+4 to 2.5e+5 (3-4 weeks long) CPU-hours for each case.

3.2 CFD Modeling of BTRA Using Methane-Air Multi Reactions Mechanism Chemistry

The CFD of the BTRA carried out using species transport model with a volumetric reaction and 2-step methane-air reaction mechanisms and utilized a hybrid finite-rate and eddy-dissipation turbulence-chemistry interaction as described previously in Section 2.1 (2.1 Development and Implementation of CFD Model for RTRA Operation). A short study was done to explore the quality and the computational cost of the combustion modeling of BTRA in methane-air mixture with more than 2-step reaction mechanism that is summarized in this section.

The detailed reaction mechanism of methane-air mixture can be modeled with 53 species and 325 reaction mechanism [53]. However, it is impractical and computationally expensive if detailed reaction chemistry is used for industrial CFD applications with complex geometry and flow interactions. In general, simplified and limited reaction mechanism schemes can be explored for CFD application and combustion modeling for premixed and non-premixed methane-air mixtures with complex geometry and limited computational resources [54]. However, down-selecting the simplified reaction mechanism is sensitive to the CFD domain, grid sizes, and limitations of CFD solver even if the computational cost is not a deciding factor. As a result, selecting a more advanced reaction mechanism scheme does not necessarily lead to a more accurate result. The hybrid Arrhenius finite-rate and Eddy-Dissipation turbulence-chemistry interaction combustion model in ANSYS Fluent was found to be a robust method for CFD modeling of the BTRA in methane-air mixture if 2-step reaction mechanism is used. The Arrhenius finite-rate model is generally inaccurate for turbulent flames due to highly non-linear chemical kinetics. The Arrhenius finite-rate model may be acceptable for combustion with relatively slow chemistry and small turbulence chemistry interaction like supersonic flames. However, the flow around and

behind the projectile in either RTRA or BTRA is fairly turbulent due to shockwave interaction between the projectile and rails or baffle walls and finite rate model alone may not be suitable for combustion modeling. On the other hand, most premixed fuel and oxidizers are fast burning which the overall rate of reaction is controlled by turbulent mixing. In general, in non-premixed flame, turbulence slowly convects and mixes fuel and oxidizer into the reaction zones where they burn quickly. But, in premixed flames, the turbulence slowly convects and mixes cold reactants and hot products rapidly in the reaction zones where the combustion is mixing-limited and chemical kinetic rates are neglected [55]. In Eddy-Dissipation model, combustion occurs whenever turbulence is present and an ignition source is not required to initiate combustion. However, this is not acceptable for the premixed mixture in RTRA and BTRA. Because, ignition must be delayed until after the flow field is established around the nose cone when the projectile starts moving in the CFD domain. As a result, the hybrid Arrhenius finite-rate and eddy-dissipation can be used since it calculates both reaction rates and the net reaction rate driven by minimum of these two rates. In other words, the Arrhenius rate acts as a kinetic switch, preventing and/or slowing down reaction before large turbulence are present. When the zone is ignited and/or contain large turbulence and has a sufficient high pressure and high temperature, the eddy-dissipation rate is generally smaller than the Arrhenius rate, and reactions are mixing-limited [55].

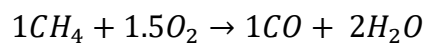
Although ANSYS Fluent allows multi-step reaction mechanisms with number of reactions more than two with the hybrid Arrhenius finite-rate and Eddy-Dissipation models, the solution may not be accurate. Because, when the number of reaction mechanism are more than two, the chemical reaction mechanism rates are based on Arrhenius rate which are different for each reaction. While, in the eddy-dissipation model, every reaction has the same turbulent rate.

Therefore, the hybrid Arrhenius finite rate with eddy dissipation model should be used only for either 1-step mechanism where the reactants convert directly to the product, or in 2-step mechanism when reactants convert to intermediate species and then the intermediate species convert to the products. If multi-step chemical reaction mechanism combustion modeling is desired, one needs to utilize the ANSYS Fluent Eddy-Dissipation Concept (EDC) combustion model with large eddy simulation (LES) computational domain characteristics [55].

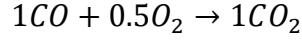
Although, a 2-step methane-air reaction mechanism was utilized with a hybrid finite-rate and eddy-dissipation combustion model to study BTRA, a few multi-step reaction mechanism models were studied and explored that are summarized here for completeness prior to down-selecting the desired 2-step reaction mechanism. In general, all of more than 2-step reaction mechanism models had the following characteristics; 1) numerically unstable and the solver did not converge per physical time step despite increasing number of sub-iteration per physical time step, 2) reducing physical time step and grid size made the simulation impractical, 3) Arrhenius rate pre-exponential factor still had to increase to start the ignition by a few orders of magnitudes, and 4) increasing the Arrhenius rate pre-exponential factor were not uniformed across all reaction mechanisms which made these modification very subjective, iterative, and impractical.

A 3-step mechanism with 5 species proposed by Westbrook-Dryer [56] was one of the first model that was explored is shown in Equation 28, Equation 29, and Equation 30. The Arrhenius rate for this mechanism is described in Equation 31 and Table 2. Note that unites of reaction parameters in tables in this section are; Calories, Moles, Liter, and Seconds.

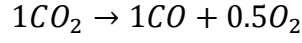
Equation 28



Equation 29



Equation 30



Equation 31

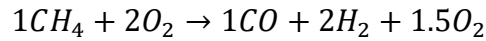
$$\sigma_{Arrhenius} = A_{Arrhenius} T^{\zeta} e^{-\frac{E_a}{RT}} [CH_4]^a [O_2]^b [CO]^c [CO_2]^d [H_2O]^e$$

Table 2 finite-rate of 3-mechanism and 5 species

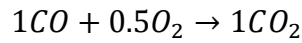
Reaction	$A_{Arrhenius}$	E_a	ζ	a	b	c	d	e
1	5.0e+11	4.8e+4	0	0.7	0.8	0	0	0
2	2.24e+12	4.1e+4	0	0	0	1	0	1
3	5.0e+8	4.1e+4	0	0	0	0	1	0

A 3-step mechanism with 6 species was used by Nusca-Kruczynski [47] to numerically simulate a large-scale ram accelerator in methane-air mixture was also explored that is shown in Equation 32, Equation 33, and Equation 34. The Arrhenius rate for this mechanism is described in Equation 35 and Table 3.

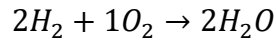
Equation 32



Equation 33



Equation 34



Equation 35

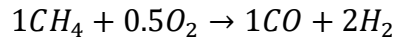
$$\sigma_{Arrhenius} = A_{Arrhenius} T^{\zeta} e^{-\frac{E_a}{RT}} [CH_4]^a [O_2]^b [CO]^c [CO_2]^d [H_2O]^e [H_2]^f$$

Table 3 finite-rate of 3-step mechanism and 6 species

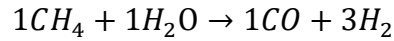
Reaction	A _{Arrhenius}	E _a	ζ	a	b	c	d	e
1	8.3e+11	3.0e+5	0	1	2	1	0	0
2	3.0e+12	4.5e+5	0	0	0.5	1	1	0
3	1e+11	3.8e+5	0	0	1	0	0	2

A 4-step mechanism with 6 species proposed by Jones-Lindstedt [57] is shown in Equation 36, Equation 37, Equation 38, and Equation 39. The Arrhenius rate for this mechanism is described in Equation 40 and Table 4.

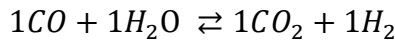
Equation 36



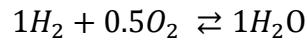
Equation 37



Equation 38



Equation 39



Equation 40

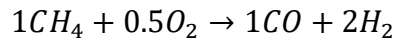
$$\sigma_{Arrhenius} = A_{Arrhenius} T^{\zeta} e^{-\frac{E_a}{RT}} [CH_4]^a [O_2]^b [CO]^c [CO_2]^d [H_2O]^e [H_2]^f$$

Table 4 finite-rate of 4-mechanism and 6 species

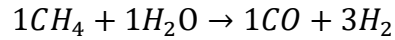
Reaction	A_{Arrhenius}	E_a	ζ	a	b	c	d	e	f
1	4.4e+11	3.0e+5	0	0.5	1.25	0	0	0	0
2	3.0e+8	3.0e+5	0	1	0	0	0	1	0
3	2.75e+9	2.0e+5	0	0	0	1	0	1	0
4	6.8e+15	4.0e+5	-1	0	1.5	0	0	0	0.25

A 6-step mechanism with 9 species was created based on Jones-Lindstedt model (4-step with 6 species) and added a dissociation reaction to generate what is known as JL-R model [54] [58] is shown in Equation 41, Equation 42, Equation 43, Equation 44, Equation 45, and Equation 46. The Arrhenius rate for this mechanism is described Equation 47 and Table 5.

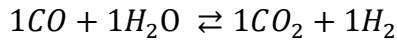
Equation 41



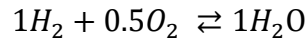
Equation 42



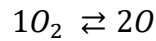
Equation 43



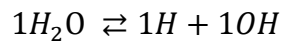
Equation 44



Equation 45



Equation 46



Equation 47

$$\sigma_{Arrhenius} = A_{Arrhenius} T^{\zeta} e^{-\frac{E_a}{RT}} [CH_4]^a [O_2]^b [CO]^c [CO_2]^d [H_2O]^e [H_2]^f [O]^g [OH]^h [H]^k$$

Table 5 finite-rate of 6 mechanism and 9 species

Reaction	A _{Arrhenius}	E _a	ζ	a	b	c	d	e	f	g	h	k
1	4.4e+11	3.0e+5	0	0.5	1.25	0	0	0	0	0	0	0
2	3.0e+8	3.0e+5	0	1	0	0	0	1	0	0	0	0
3	2.75e+9	2.0e+5	0	0	0	1	0	1	0	0	0	0
4	6.8e+15	4.0e+5	-1	0	1.5	0	0	0	0.25	0	0	0
5	1.5e+9	1.1e+5	0	0	1	0	0	0	0	0	0	0
6	2.3e+22	1.2e+5	-3	0	0	0	0	1	0	0	0	0

The CFD of the rest of BTRA research carried out using species transport model with a volumetric reaction and 2-step methane-air reaction mechanisms (hybrid finite-rate and eddy-dissipation turbulence-chemistry interaction model) and N_2 species remained neutral and did not react with reactants and products and only acted as a 3rd body effect with a small 3rd body efficiency. The author's recommendation for future researchers is to use Eddy-Dissipation Concept combustion model with a LES solver when grid sizes are adequate for LES calculations and when more computational resources are available.

3.3 Geometries Used in CFD Modeling of BTRA, Objectives, and Test Matrices

Investigating the effects of projectile interactions with baffle tubes is one role of the CFD simulations currently in progress at University of Washington. Simulations of reactive flows with

ANSYS Fluent software [42] reported in Section 3 (CFD Modeling of Baffled Tube Ram Accelerator in Reactive Flow) are the transient flow field characteristics and thrust generation over two types of projectiles (short and long shoulder) in various BTRA configurations.

The baseline projectile, also referred to as the short shoulder projectile, is shown in Figure 43. The alternative projectile (long shoulder projectile) is shown in Figure 44. Both projectiles are axisymmetric without fins with a 15-degree nose cone and 12-degree tail cone frustum accordingly. The baseline projectile shoulder spans 2 baffles length (2 chamber length) and 3 baffle wall thickness based on variables described in Figure 6. The long shoulder projectile (alternative projectile) spans 3 chamber length and 4 baffle wall thickness respectively. Both projectiles have the same outer-diameter of 1.38" as shown in Figure 43 and Figure 44.

Majority of the CFD simulations of BTRA carried out inside the BTRA501 configuration which had a minimum bore inner-diameter of 1.505" and maximum outer-diameter of 2.5" as shown in Figure 45. The other BTRA configuration used in CFD simulation was a BTRA111 configuration which had identical inner-diameter as the BTRA501 (1.505"), but had a maximum 3.0" outer-diameter as shown in Figure 46. Both BTRA501 and BTRA111 had annular normal baffles that were like washers that protrude from the inner wall of the tube and are perpendicular to the direction that projectile moved. In addition, both BTRA501 and BTRA111 configurations provided a minimum gap of 0.0625" between the projectile shoulder and the minimum bore clearance as the projectile moved in these configurations.

Most of experiments tested at University of Washington have been carried out with P380-2B-12-15 (short shoulder projectile) or P30-3B-12-15 (long shoulder projectile) inside a BTRA501 and/or a BTRA111 configuration at different premixed methane-air mixtures and/or at different

velocities. All CFD simulations reported in Section3 had a fixed premixed methane-air mixture of $1\text{CH}_4+2\text{O}_2+4.67\text{N}_2$ (stated for clarity).

Other BTRA configuration such as BTRA601 with a maximum 2.0" outer-diameter also has been tested experimentally as shown in Figure 47. Only one CFD simulation was carried out inside the BTRA601 when the baseline projectile moved at a constant velocity of 1.0 km/s and it unstarted very early on during the simulation and then the CFD simulation was terminated. Also, there was an attempt to simulate another CFD case using the baseline projectile inside a notional BTRA602 configuration (not shown in a figure in this report) with maximum 2.2" outer-diameter. This case unstarted similar to BTRA601 configuration when the projectile moved at 1.0 km/s constant velocity. However, the unstart characteristics occurred later relative to BTRA601 configuration case. One more BTRA configuration explored using CFD simulation was a domain starting with BTRA111 configuration from Baffle#1 to Baffle#39 (3.0" outer-diameter) and then morphing to the BTRA501 from Baffle#40 to Baffle#70 (2.5" outer-diameter). BTRA111-to-501 Configuration was designed to examine impact of the BTRA configuration change on the performance of the projectile when it moved from one configuration to another one.

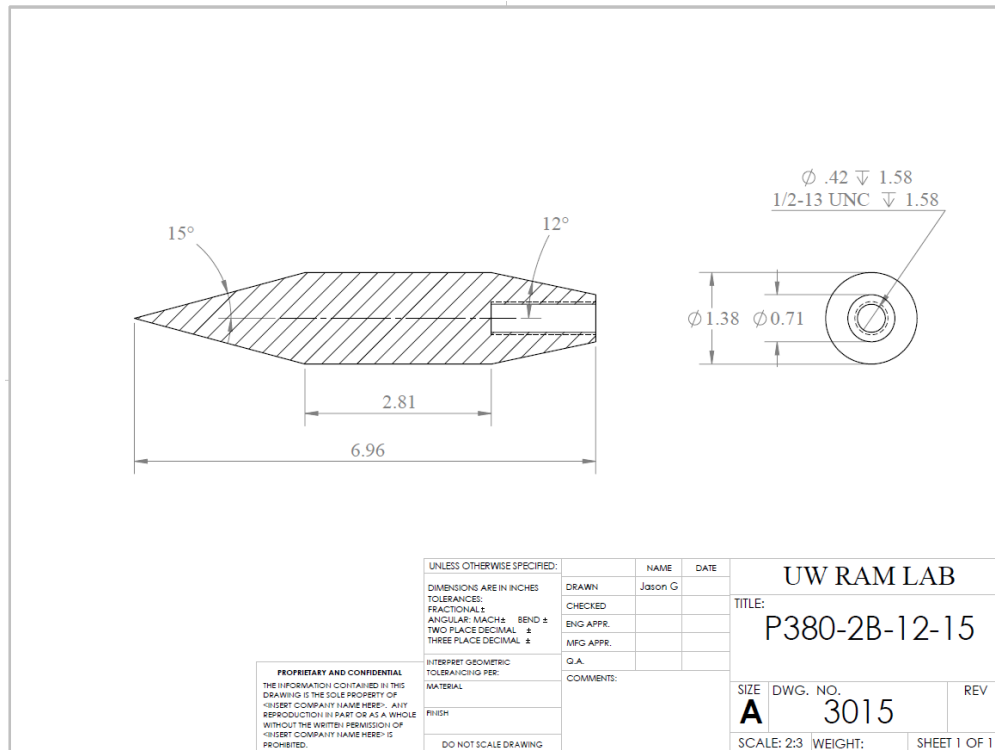


Figure 43 P380-2B-12-15 axisymmetric projectile

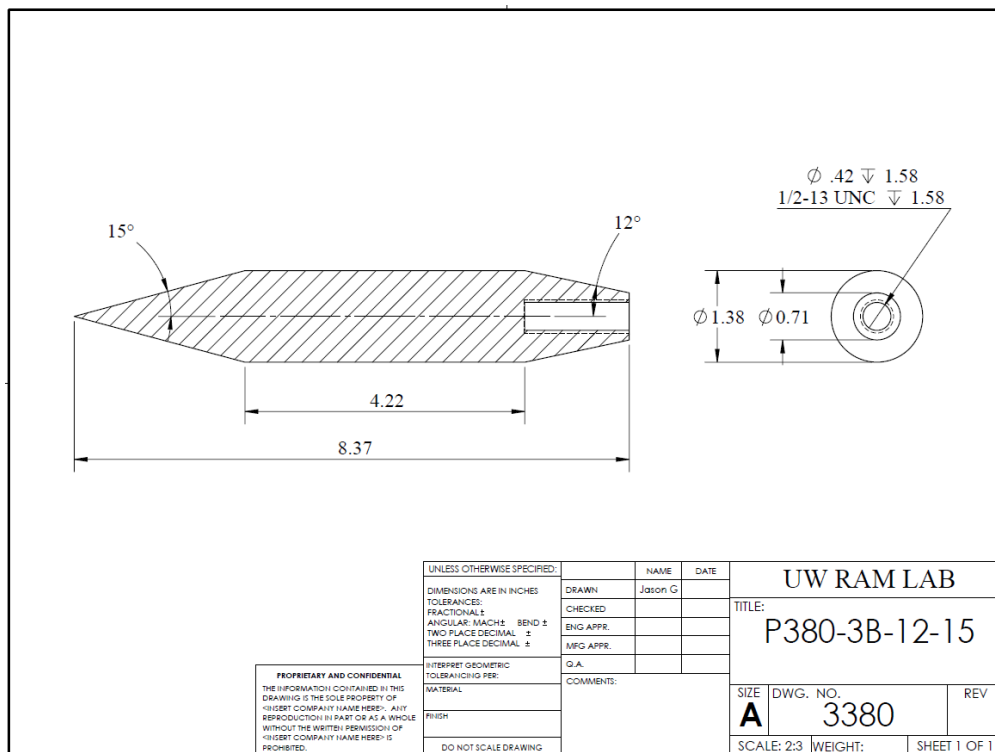


Figure 44 P380-3B-12-15 axisymmetric projectile

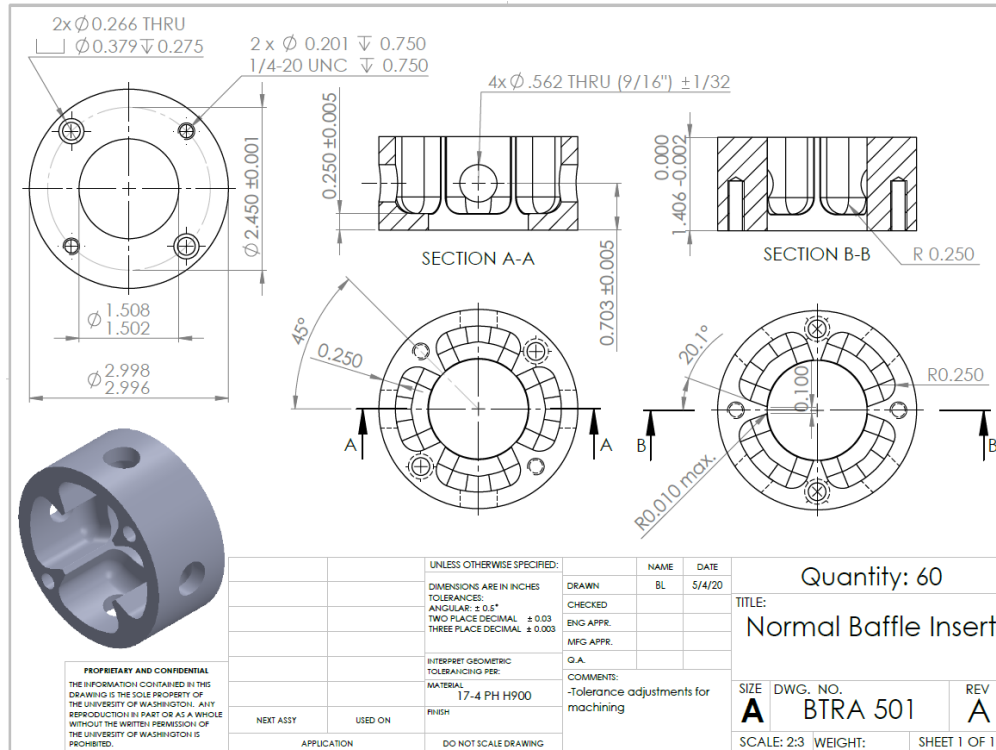


Figure 45 BTRA501 configuration

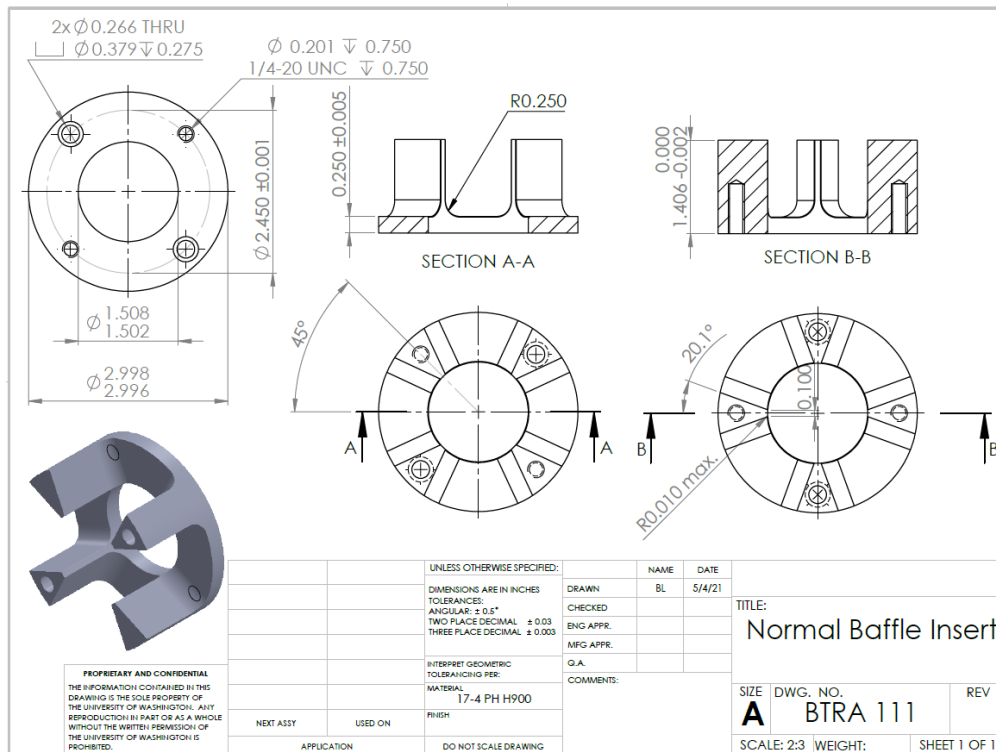


Figure 46 BTRA111 configuration

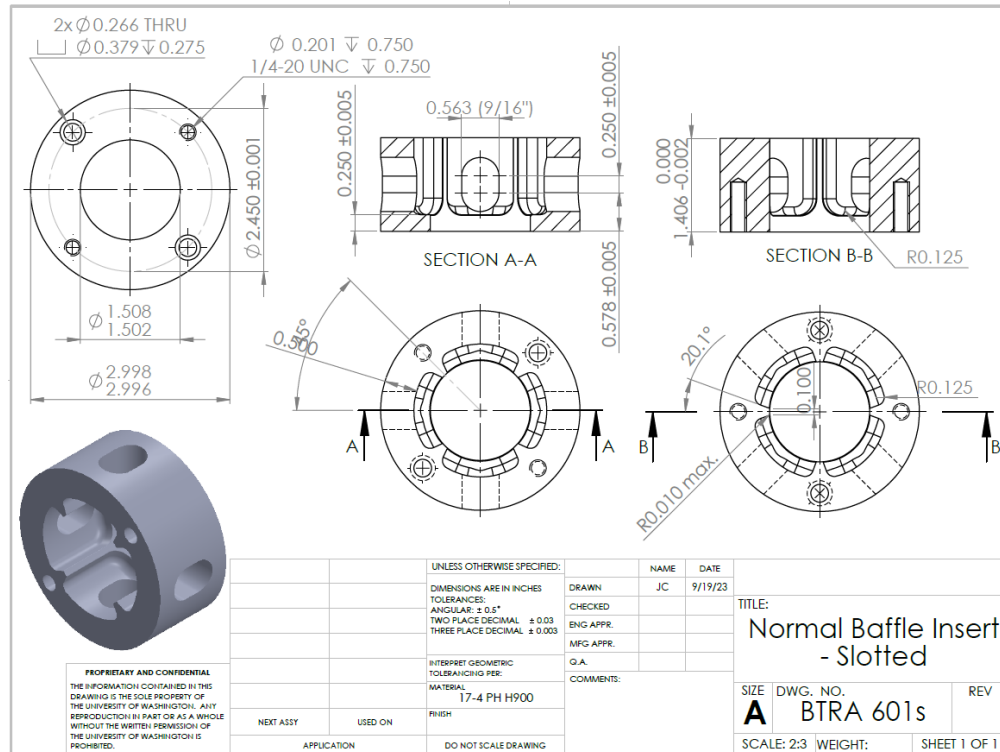


Figure 47 BTRA601 configuration

For all CFD cases, instantaneous thrust was determined by integrating pressure and shear forces acting on the four projectile segments (nose, shoulder, tail, and base). The corresponding non-dimensional thrust was calculated by normalizing the instantaneous thrust with the fill pressure and reference minimum bore cross section area.

There were 5 main objectives to use CFD to determine the characteristics of BTRA configurations and projectile's performance relative to the experimental results conducted at University of Washington;

1. Determine impact of varying outer-diameter of BTRA when the baseline projectile (short shoulder projectile) moved at a constant velocity of 1.0 km/s. See Section 3.5 (3.5 Impact

of Outer-Diameter Variation of BTRA on The Performance) for more information and Table 6 that shows the status of each case.

2. Determine impact of velocity variation on non-dimensional thrust on the baseline and alternative projectiles inside BTRA501 configuration. The CFD data was collected on the baseline projectile moving at constant velocity of 1.0, 1.1, 1.2, and 1.4 km/s. While, CFD simulations were conducted on the alternative projectile (long shoulder) at constant velocity of 1.0 and 1.2 km/s accordingly. See Section 3.6 (3.6 Impact of Velocity Variation on Non-Dimensional Thrust) for more information and Table 7 that shows the status of each case.
3. Determine impact of constant acceleration on non-dimensional thrust on the baseline and alternative projectiles. The baseline projectile accelerated from 1.0 to 1.1 km/s with a constant acceleration of $\sim 8000g$ (m/s^2) and from 1.0 to 1.2 km/s with a constant acceleration of $\sim 19656g$ (m/s^2) inside BTRA501. The alternative projectile accelerated from 1.0 to 1.2 km/s with a constant acceleration of $\sim 19656g$ (m/s^2) inside BTRA501. See Section 3.7 (3.7 Impact of Constant Acceleration on Non-Dimensional Thrust) for more information and Table 8 that shows the status of each case.
4. Find an analytical method using CFD simulation data to estimate the location of the theoretical thermally choked region behind the projectile when the projectile moved at a constant velocity.
5. Find the thrust efficiency for a given projectile for various BTRA configurations, i.e., the ratio of the projectile thrust normalized by the sum of baffle drag and projectile thrust.

See Section 3.8 (3.8 Determining Thermally Choked Region and Thrust Efficiency) for more information.

Table 6 test matrix: outer-diameter variation of BTRA with the baseline projectile

	BTRA111	BTRA501	BTRA111-to-501	BTRA601	BTRA602
OD	3.0"	2.5"	3.0"-to-2.5"	2.0"	2.2"
Velocity	1.0 km/s	1.0 km/s	1.0 km/s	1.0 km/s	1.0 km/s
Status	Started	Started	Started	Unstarted	Unstarted

Table 7 test matrix: velocity variation impact on baseline and alternative projectile in BTRA501 configuration

	1.0 km/s	1.1 km/s	1.2 km/s	1.4 km/s
Baseline Projectile	Started	Started	Started	Started
Alternative Projectile	Unstarted	-----	Started	-----

Table 8 test matrix: constant acceleration impact on baseline and alternative projectile in BTRA501 configuration

	~8000g m/s² (1.0 to 1.1 km/s)	19656g m/s²(1.0 to 1.2 km/s)
Baseline Proj.	Started	Started
Alternative Proj.	-----	Started

A systematic CFD setup and data collection methodology was required to estimate the location of the theoretical thermally choked region and allow a more efficient CFD data analysis. Such setup was found in a few CFD domain design iterations after the flow field variables of interest were identified. Also, there was an interest to collect wall pressure information inside

some baffle chambers and compare the CFD result against the experimental pressure transducer signal.

A sideview of the baseline projectile in Figure 48 shows an example of the flow field at a desired dynamic range (static pressure: 300-3000 psig) when the projectile passed through Baffle#28. As mentioned before, all BTRA configurations consist of 70 baffles and force data was collected on Baffle#15 thru Baffle#70 at every physical time step. Each baffle chamber consists of 4 unique walls, i.e., aft face wall, upper face wall, forward face wall, and shoulder, marked by a unique value indicating the baffle number. For example, these walls are shown with magenta, green, cyan, and red dotted lines in Figure 48.

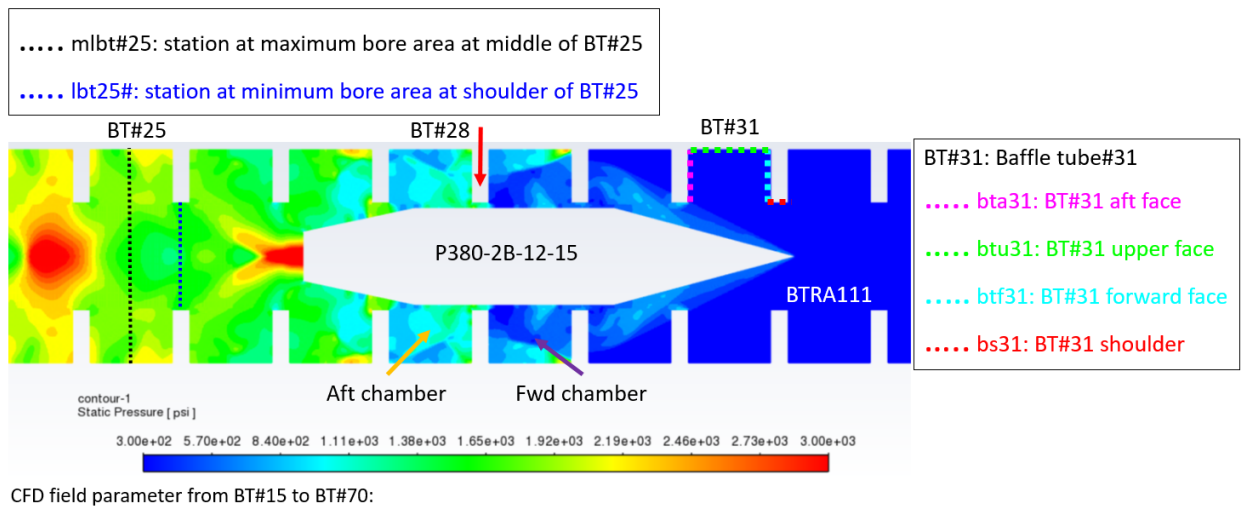


Figure 48 static pressure field of P380-2B-12-15 projectile inside BTRA111

Also, an integrated pressure data on each wall of the baffle chamber was collected. In addition, the force data was collected on 4 segments of the projectile (nose, shoulder, tail and base) at each time step similar to RTRA study. In addition to wall pressure and force data over any physical viscous surface in CFD domain, other unique data were collected on virtual cross

sections. These virtual cross sections were located at minimum and maximum bore area from Baffle#15 thru Baffle#70. The flow field quantities collected at these virtual cross sections provided information to analytically estimate the location of theoretical thermally choked region behind the projectile. These flow field quantities were; 1) area weighted average pressure, 2) area weighted average axial velocity, 3) area weighted average Mach number, 4) area weighted average density, and 5) area weighted average temperature at both minimum and maximum bore area between Baffle#15 thru Baffle#70. The virtual cross sections of Baffle#25 at minimum and maximum bore area are shown with dark blue and black dotted line in Figure 48.

More than 1035 flow field quantities at each physical time step were collected for each CFD case to perform an efficient post-processing and data analysis. These data were written in an ASCII text file format that is readable in MATLAB [59] or any other data analysis tool. The size of each of ASCII file was under 1.0 gigabyte (GB).

3.4 CFD Modeling of BTRA and Available Data

This section provides a content for what CFD flow field quantities that are typically shown in latter sections, what plots can be generated, and rationales behind CFD post-processing activities. First, some gas mixture property, reference dimensions, and Reynolds number for BTRA CFD cases are referenced. Second, an example of non-dimensional thrust breakdown versus time plot is provided that is frequently used for CFD case comparisons. Third, a definition of an “event” is provided to identify a particular time of interest for CFD post-processing analysis. Using the event definition, a few flow field maps such as static pressure, static temperature, CO-mole fraction and axial velocity are shown to describe how the flow field evolves in a BTRA configuration. Lastly, a

process is described to estimate the location of the theoretical thermally choked region behind the projectile base by using the event definition criteria. The Reynold number of a BTRA configuration with a P380 projectile is about $4.43\text{e}+7$ calculated based on Equation 48. The projectile diameter (reference length) is $3.5\text{e}-2$ m (1.38”) and the reference velocity is 1.0 km/s inside unburnt $1\text{CH}_4+2\text{O}_2+4.67\text{N}_2$ mixture at 300 K fill temperature and 20.4 atm (300 psig) fill pressure. The average density of unburnt methane-air at reference fill pressure and temperature is $2.28\text{e}+1$ kg/m³ with gas constant of $R=3.02\text{e}+2$ m³Pa/kgK using ideal gas Equation of State (Equation 4). The dynamic viscosity of the mixture, μ_{mix} , is about $1.8\text{e}-5$ kg/sm and approximated by Equation 49 where χ_i , μ_i , and M_i are mole fraction, dynamic viscosity, and molecular weight of each species at 300 K [60]. The absolute dynamic viscosity is linearly interpolated for CH₄, O₂, and N₂ between 290 to 320 K using available thermodynamic table data [61].

Table 9 shows the gas properties and Reynolds number associated with the BTRA setup.

Equation 48

$$Re_{BTRA} = \frac{\rho_{mix} velocity_{ref} length_{ref}}{\mu_{mix}}$$

Equation 49

$$\mu_{mix} = \frac{\sum \mu_i \chi_i \sqrt{M_i}}{\sum \chi_i \sqrt{M_i}}$$

Table 9 gas mixture property, reference dimensions, and Reynolds number

Quantity	Dimension	Value
Unburnt mixture	N/A	1CH ₄ +2O ₂ +4.67N ₂
Fill pressure	atm	2.04e+1
	(psig)	(3e+2)
Fill temperature	K	3e+2
Mixture mass (average)	g/mol	2.75e+1
Density (average)	kg/m ³	2.28e+1
$\mu_{CH_4}@ 300\ K$	kg/sm	1.12e-5
$\mu_{O_2}@ 300\ K$	kg/sm	2.07e-5
$\mu_{N_2}@ 300\ K$	kg/sm	1.79e-5
$\mu_{mix}@ 300\ K$	kg/sm	1.8e-5
$velocity_{ref}$	m/s	1e+3
$length_{ref}$	m	3.5e-2
	(inch)	(1.38)
BTRA Reynolds number	N/A	4.43e+7

In the current CFD setup of BTRA configuration, instantaneous thrust over the projectile body is collected by integrating pressure and shear forces acting on the four projectile segments (nose, shoulder, tail, and base). The non-dimensional thrust is calculated by normalizing the

instantaneous thrust with the fill pressure and reference minimum bore cross section area. An example of a non-dimensional thrust versus physical time step of P380-2B-12-15 inside BTRA111 configuration is shown in Figure 49. In this figure, the thrust generated by the base, head (nose cone), shoulder and tail are shown in red, green, magenta and blue lines and the total thrust is shown with black line respectively. This simulation ran about 4.3×10^4 time-steps at 5×10^{-8} s per time step. The head (nose cone) only generated drag with a relatively constant non-dimensional thrust of -2.0-unit. While, the base and tail of the projectile generated thrust entirely but did not reach a quasi-periodic solution during the simulation. The total non-dimensional thrust reached around 4.0-unit by end of the simulation.

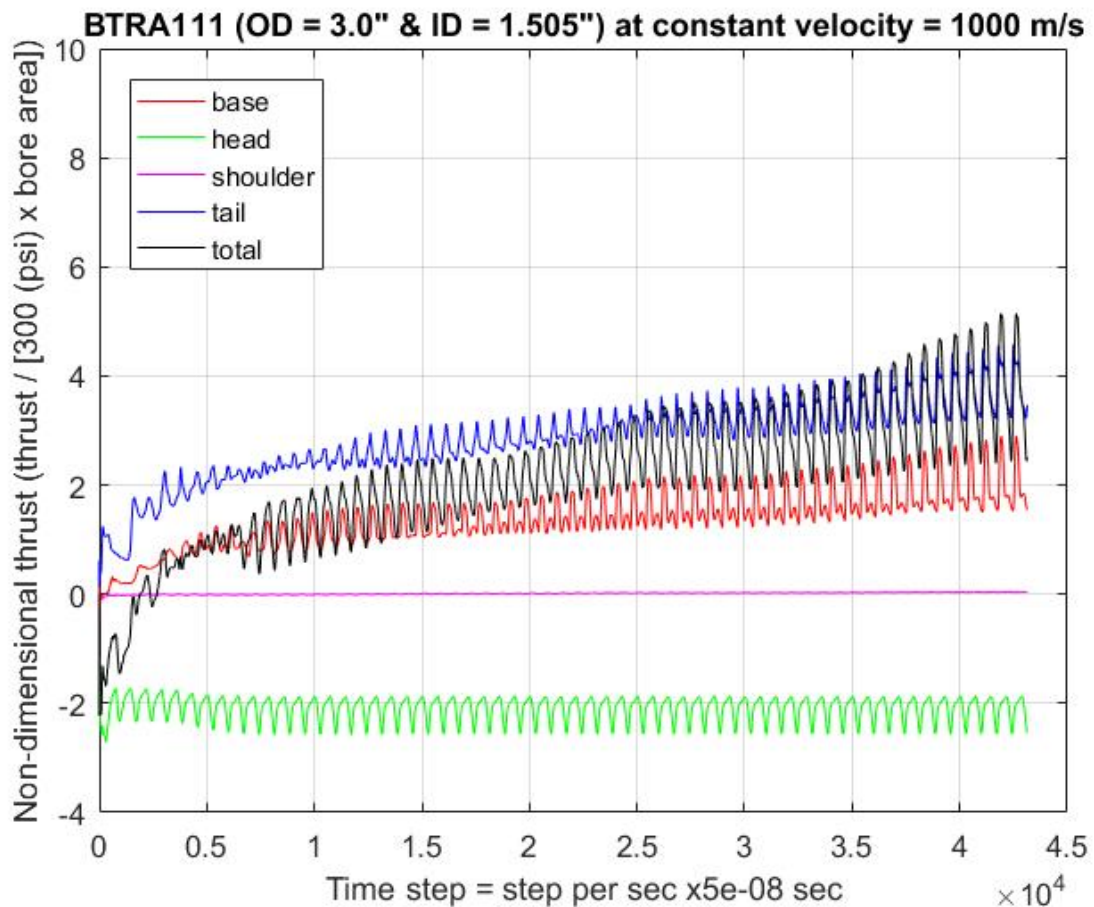


Figure 49 non-dimensional thrust breakdown vs. time step example

There is a desire to identify a time of interest as the projectile passes through any given baffle to examine the flow interaction between the projectile and near the baffle chamber of interest. Since force information are collected on all 4 wall segments of Baffle#15 thru Baffle#70, it is possible to define a criterion or an “event” to examine where the projectile is at that time. When a projectile passes through a BTRA configuration, some of the kinetic and chemical energy is used to exert force (pull or push as a function of time) across any baffle. For example, the total force acting on Baffle#58 is sum of the forces acting on forward face wall of the Baffle#58 and aft face wall of the Baffle#59 if the force acting on the shoulder wall of Baffle#58 is ignored. When, the projectile has not reached the Baffle#58 yet, only the static fill pressure is felt across Baffle#58, so the net force acting on Baffle#58 is zero. As soon as leading shockwave from the projectile nose cone enters the Baffle#58 chamber, the net force across two adjacent walls of Baffle#58 starts to oscillate manifesting a pull-push force. As a result, the net force reaches a maximum and a minimum value as a function of time before it oscillates around zero net force.

An event is defined as following; “finding the exact time step when any given baffle experiences the maximum push net force, i.e., the maximum net force pushing on walls of a chosen baffle in the same direction as the projectile moves”. Note that finding the exact time of minimum net force (maximum pull force) is also an interesting event since the time interval between these two phenomena vary for different BTRA configurations. A non-dimensional force acting on a given baffle wall can be defined similar to that of the non-dimensional thrust by normalizing the instantaneous baffle force with the fill pressure and reference minimum bore cross section area. The non-dimensional thrust on the projectile and the baffle force information provide a relative force distribution on the projectile for any given baffle as a function of time.

Figure 50 is an example of identifying the maximum push net force acting across Baffle#58 walls that occurs at 37510th time step (5e-8 s per time step), shown with black asterisk sign, inside BTRA111 configuration when the short shoulder projectile moves at 1.0 km/s. At this event, the middle of the projectile shoulder is roughly below Baffle#58 and this baffle experiences a ~9.6-unit non-dimensional push net force while the projectile experiences ~3.4-unit non-dimensional thrust. The breakdown of the non-dimensional projectile thrust on the base, head, shoulder and tail are 1.5, -2.2, 0.03, and 4.1-units accordingly. The non-dimensional minimum push net force (maximum pull net force) across Baffle#58 walls occurs at 42197th time step, shown with magenta open circle sign, where the projectile has moved roughly by 6-7 baffles relative to event#1.

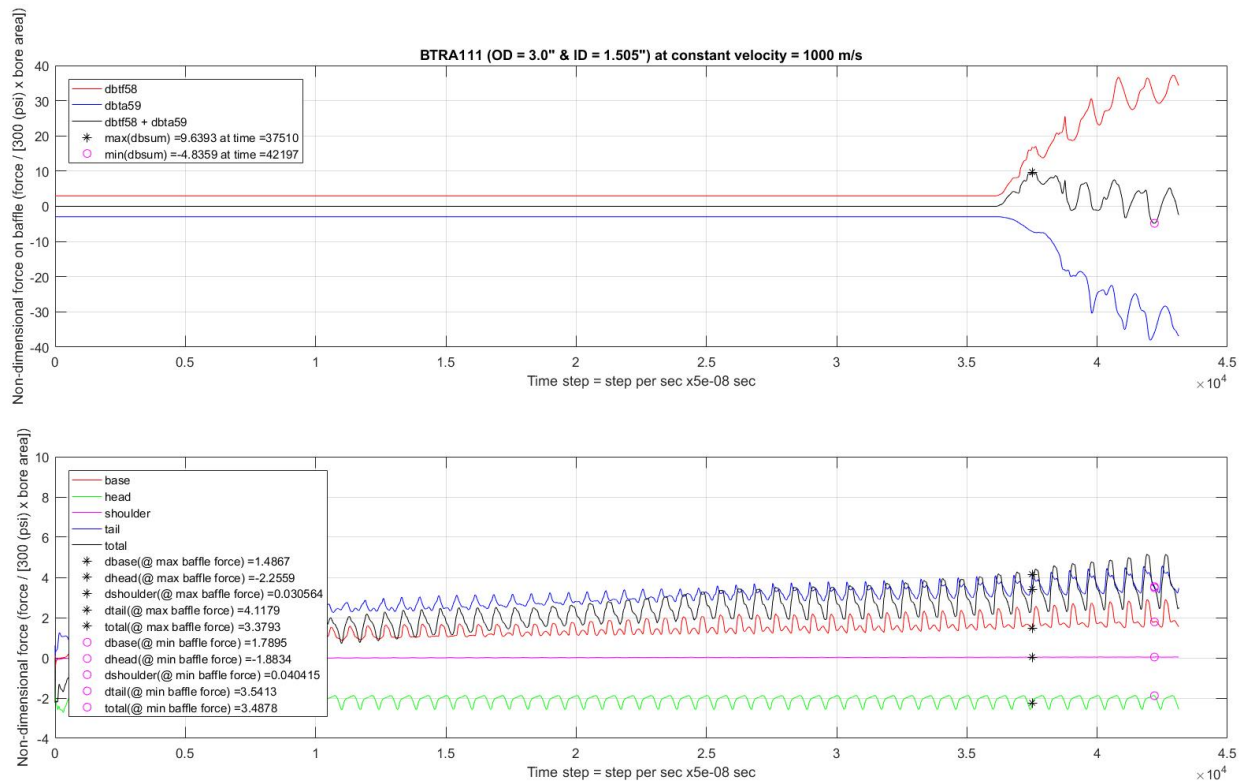


Figure 50 non-dimensional force signal on Baffle#58 in BTRA111 and non-dimensional thrust breakdown on P380-2B-12-15 at 1.0 km/s

Although ASCII data file contains information at every physical time step for each CFD case, the CFD solution files for flow visualization, restarting and/or continuing a simulation are available only at every 100 physical time-step to manage data generation and data storage purposes. As a result, when an event is identified for a case, the closest CFD solution file to that event is used for the flow visualization. In general, four flow fields maps are used in this report to discuss various phenomena using a fixed dynamic range to be able to compare cases; 1) static pressure contour at 300 to 4300 psig, 2) static temperature contour at 300 to 4300 K, 3) CO-mole fraction at 0 to 2.5×10^{-2} , and 4) axial velocity at 0 to 2.0 km/s.

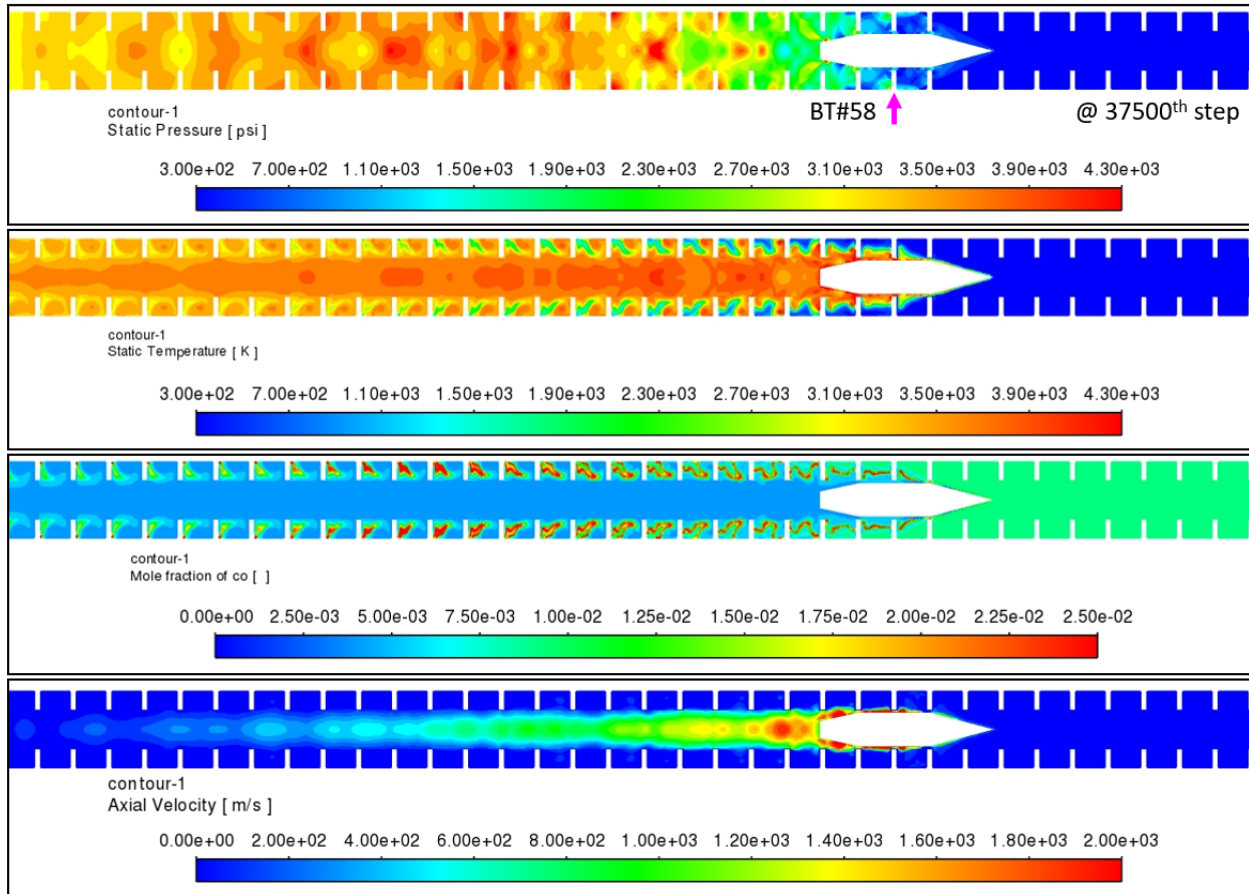


Figure 51 static-pressure, static-temperature, CO-mole fraction, and axial velocity maps of P380-2B-12-15 inside BTRA111 at 1.0 km/s near BT#58 at approximately 37500th time step (5×10^{-8} s per time step)

Figure 51 shows an example how static pressure, static temperature, CO-mole fraction, and axial velocity flow fields look like where Baffle#58 experiences maximum push net force. During this event, the middle of projectile shoulder is roughly under the Baffle#58. The static pressure map shows that a relatively a high-pressure region with approximately 2 to 2.5-times of the projectile length is following the projectile. The high-pressure region starts about one projectile length behind the base. The static temperature contour shows how combustion advances near the projectile and how it evolves 10-15 baffles behind the base in this case. The CO-mole fraction contour is a good indicator where the turbulent combustion occurs. CO is an intermediate species that must be generated and consumed during the combustion process. Therefore, a high concentration trace of CO shows where strong reactive regions are. CO-mole fraction map shows how CO is generated on the projectile shoulder and then more CO is generated and consumed in the high-pressure region behind the projectile base. The axial velocity contour from 0 to 2.0 km/s shows that the bulk of the fluid moves in the same direction as the projectile mainly inside the bore. There are pockets of high velocity regions right behind the base and on the tail of the projectile that moves even faster than the projectile in the laboratory frame of reference at this time step. Note that any region shows in dark blue in axial velocity contour is not moving forward, but it does not mean it does not move backward relative to the projectile.

Using an event definition, one can freeze the location of the projectile as function of time near any given relevant baffle and estimate the location of the theoretical thermally choked section a few baffles behind the base through an iterative process described below.

A control volume shown below is drawn around P380-2B-12-15 projectile inside BTRA111 configuration when the projectile moves at 1.0 km/s. The static pressure field is extracted around

event#1, when the Baffle#58 experiences maximum push net force around 37510th time step. In order to find the thermally choked section in BTRA, two fundamental stations, i.e., Station#1 and Station#2, must be identified. Station#1 is a location ahead on the projectile nose cone and contains some undisturbed flow ahead of the projectile to facilitate numerical analysis. Station#2 is a section a few baffles downstream of the projectile base that must satisfy the momentum equation and it is identified through an iterative process. If one extends the control volume by a few baffles upstream, e.g. 4 baffles, to contain the entire projectile nose cone and some undisturbed flow ahead of the projectile using event#1 definition, then Station#1 location is identified as shown in Figure 52 below.

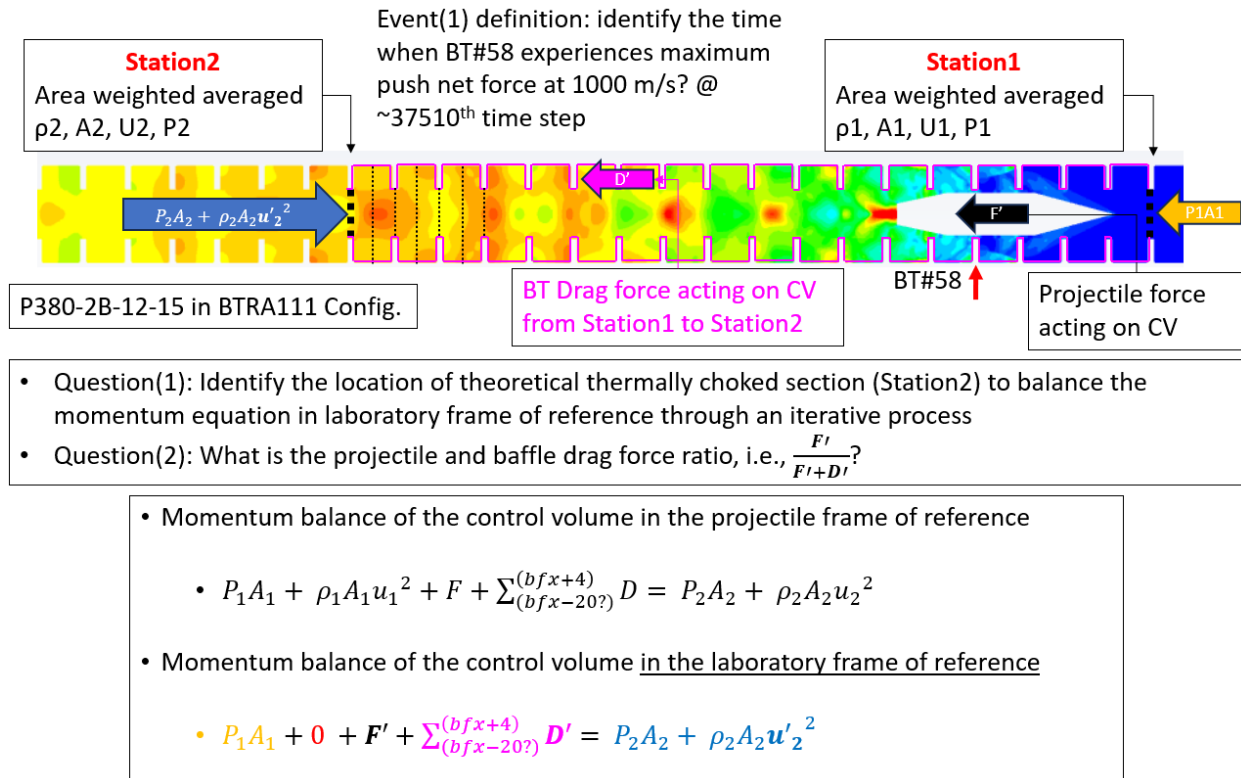


Figure 52 the process to estimate theoretical thermally choked section inside BTRA

For example, Station#1 is at Baffle#62 when Baffle#58 experiences the maximum push net force (event#1). If Station#2 is at X-number of baffles behind the Baffle#58 (to be determined analytically and iteratively), then momentum equation for a control volume containing the projectile moving at a constant velocity in a BTRA can be written as Equation 50 or Equation 51 in the projectile and the laboratory frame of references accordingly. The term $\rho_1 A_1 u_1^2$, in laboratory frame of reference is zero since u_1 is zero. In other words, no flow is convected into the control volume in the laboratory frame of reference at Station#1. The term $P_1 A_1$ is known and F' is calculated at every time step. As mentioned before, all area averaged flow field quantities are calculated at every physical time step at minimum and maximum bore area across sections from Baffle#15 thru Baffle#70 (virtual cross sections). The term u'_2 is the area averaged axial velocity of the moving fluid at Station#2 in laboratory frame of reference. One can guess the location of Station#2 is X-number of baffles behind Baffle#58 and extract area averaged pressure, density, and velocity to calculate the right-hand side term of momentum equation. Then, integrate all drag forces from Baffle#58+4 to Baffle#58-X and check if the left-hand side of the momentum equation equates and/or get closer to the right-hand side. Then, repeat this process until the delta between the right-hand side and left-hand side of the momentum equation becomes minimal and/or zero a few baffles behind the projectile. This process is a first order analytical method the estimate the location of the theoretical thermally choked section using CFD data with the assumption that such section is near the minimum bore area behind the projectile base and the flow is thermally choked. The static pressure, static temperature, CO-mole fraction and axial velocity flow field information also facilitate to justify the location of theoretical thermally choked region visually. For example, the rapid reduction of CO-mole fraction trace inside some baffle chambers is a good

indicator that the thermally choked region is near baffles where CO-mole fraction quickly vanishes. Also, the end tail of forward moving fluid in the BTRA bore and behind the projectile base in the axial velocity map suggests where the thermally choked region is. The static pressure contour map suggests where the pressure fluctuation reduces downstream of the maximum peak pressure region, that is where the flow is thermally choked.

Equation 50

$$P_1 A_1 + \rho_1 A_1 u_1^2 + F + \sum_{BT\#n-x}^{BT\#n+4} D = P_2 A_2 + \rho_2 A_2 u_2^2$$

Equation 51

$$P_1 A_1 + 0 + F' + \sum_{BT\#n-x}^{BT\#n+4} D' = P_2 A_2 + \rho_2 A_2 u_2'^2$$

If this calculation is performed for the short shoulder projectile moving at a constant velocity of 1.0 km/s inside the BTRA111, then the thermally choked section is estimated to be around Baffle#41 while the Baffle#58 experiences the maximum push net force (event#1) at 37510th time step. At this time, the nose cone of the projectile is near Baffle#61, its shoulder is at Baffle#58 and its base is near the Baffle#56. As a result, thermally choked section is estimated to be roughly 15 baffles behind the base of the projectile at event#1. By estimating the location of thermally choked section, the thrust force on the projectile, F' , can be compared relative to the sum of the drag force from Station#1 to Station#2 and the thrust force on the projectile, $F' + D'$, to define a thrust efficiency ratio matrix as is shown in Equation 52.

Equation 52

$$Thrust_efficiency_{BTRA} \stackrel{\text{def}}{=} \frac{F_{projectile}'}{F_{projectile}' + D_{from STN\#1 \text{ to } STN\#2}'}$$

The thrust efficiency or force ratio for the short projectile moving at 1.0 km/s inside of the BTRA111 at 37510th time step is about 31%. The delta between the left-hand and right-hand sides of the momentum equation, in the laboratory frame of reference, versus the baffle location with the static pressure, static temperature, CO-mole fraction and the axial velocity fields are shown in Figure 53, Figure 54, Figure 55, and Figure 56 accordingly. The projectile nose cone, shoulder, and base of the projectile are shown with the blue cross, circle, and triangle respectively. While, the estimated thermally choked section is shown with the black triangle on these plots showing the thermally choked section is roughly 15 baffles behind the projectile base in this case.

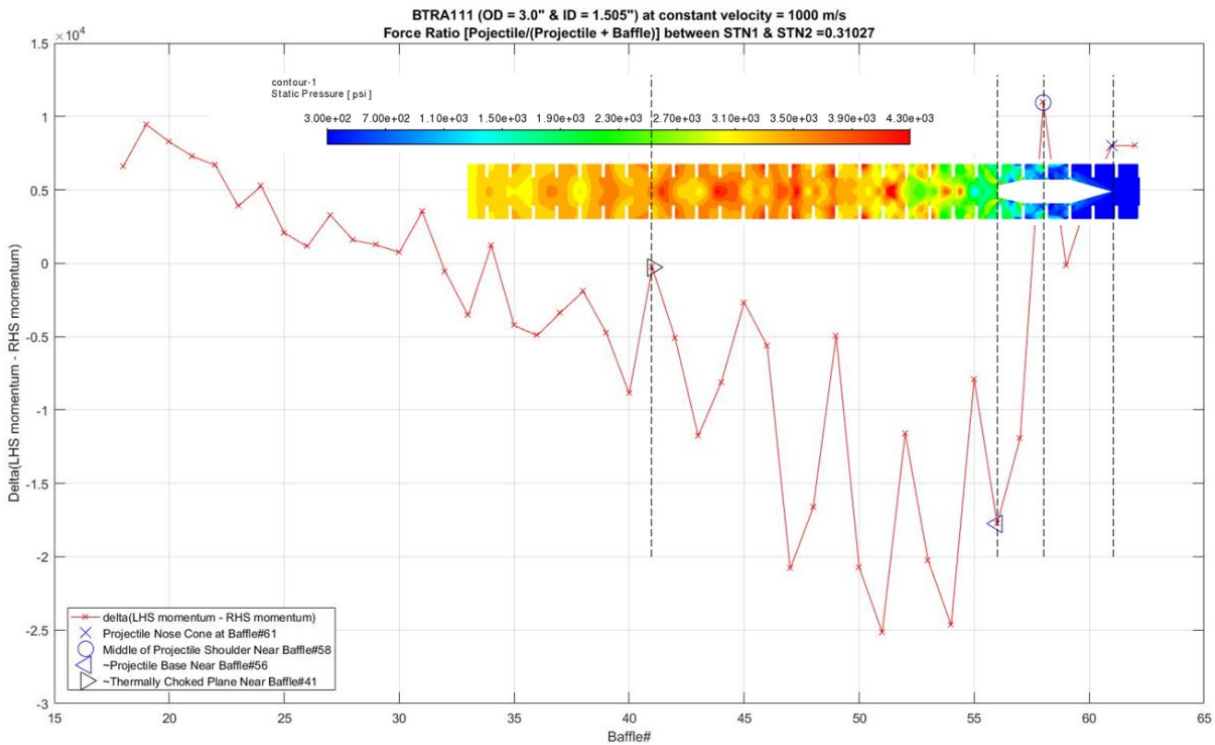


Figure 53 thermally choked location of P380-2B inside BTRA111 at 1.0 km/s and static pressure field

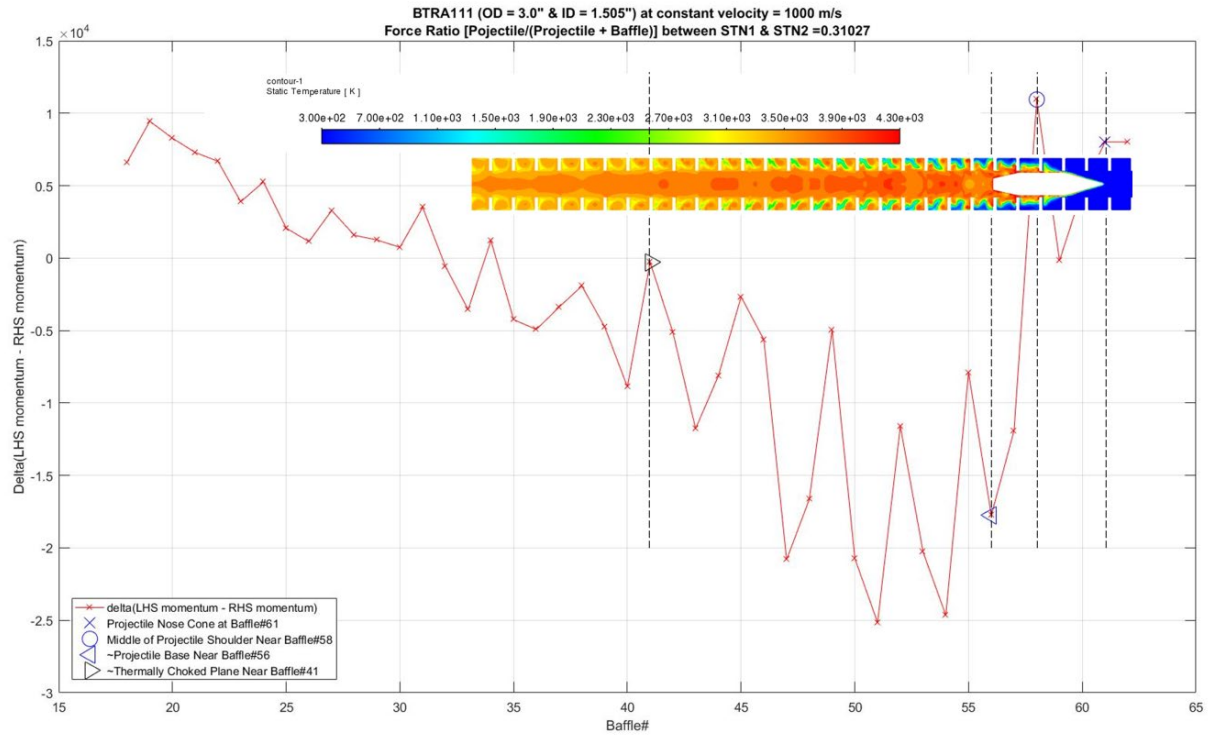


Figure 54 thermally choked location of P380-2B inside BTRA111 at 1.0 km/s and static temperature field

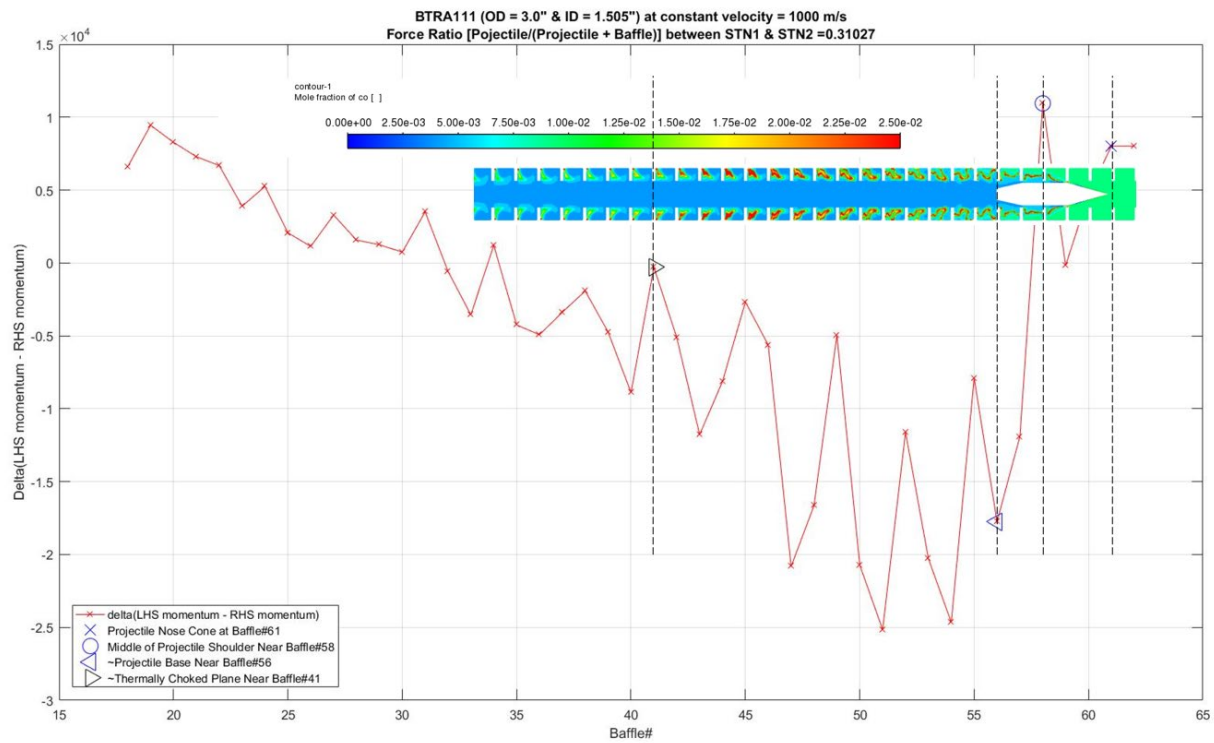


Figure 55 thermally choked location of P380-2B inside BTRA111 at 1.0 km/s and CO-mole fraction field

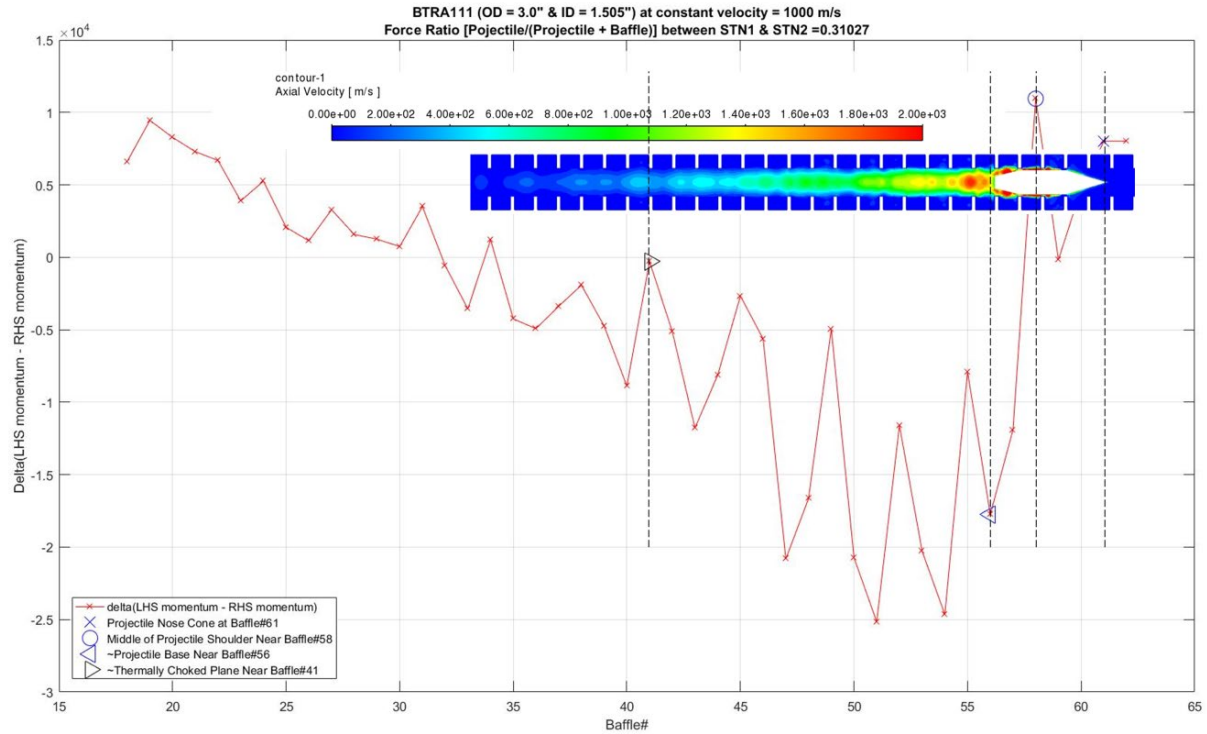


Figure 56 thermally choked location of P380-2B inside BTRA111 at 1.0 km/s and axial velocity field

One of the advantages of simulating the BTRA in the laboratory frame of reference is that the velocity vector field provides some insights about how the flow moves around the projectile, inside baffle chambers, minimum gap area, and overall projectile-chamber flow interactions. The velocity vector field also shows how the circulation pattern inside the chambers emerges. These patterns can be informative for the future BTRA and projectile optimization. A few examples of the velocity vector field colored by the magnitude of axial velocity are shown in Figure 57, Figure 58, Figure 59, and Figure 60 as P380-2B-12-15 moves at 1.0 km/s inside BTRA111 and passes Baffle#56 from 36100th to 37500th time step. When the projectile moves forward, it pushes the fluid around the nose cone into the upcoming baffle chamber and the flow expands out. The forward moving high velocity pockets near the shoulder suggest that flow surges into the

minimum gap area at a velocity higher than the projectile velocity momentarily. Then, the flow expands outward and moves toward the upper right corner of the first chamber, without a noticeable circulation pattern, as the projectile's shoulder seals against the first chamber. Then, a counter-clockwise circulation pattern emerges inside the 2nd to 4th chambers where the projectile base is located. These observations suggest implementing fillet radii on the upper corners of the chamber can facilitate flow circulation and promote or demote combustion if needed. The flow circulation inside chambers is stronger near projectile's body and it reduces drastically a few baffles behind the base. The flow inside the bore volume has a wavy pattern; if the flow circulation inside the baffle chamber is constructive and counter-clockwise, flow constricts toward the center of the bore area in a repeatable pattern.

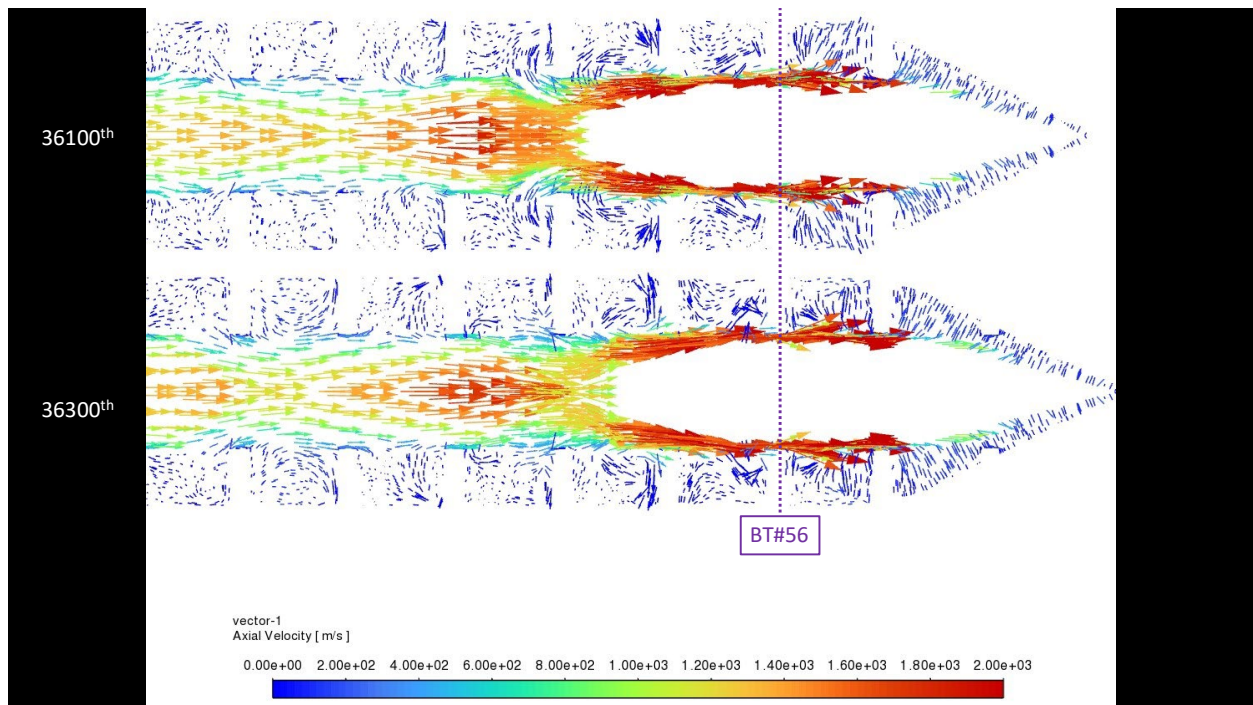


Figure 57 velocity vector field colored by magnitude of the axial velocity of P380-2B-12-15 inside BTRA111 at 1.0 km/s (36100th to 36300th time step)

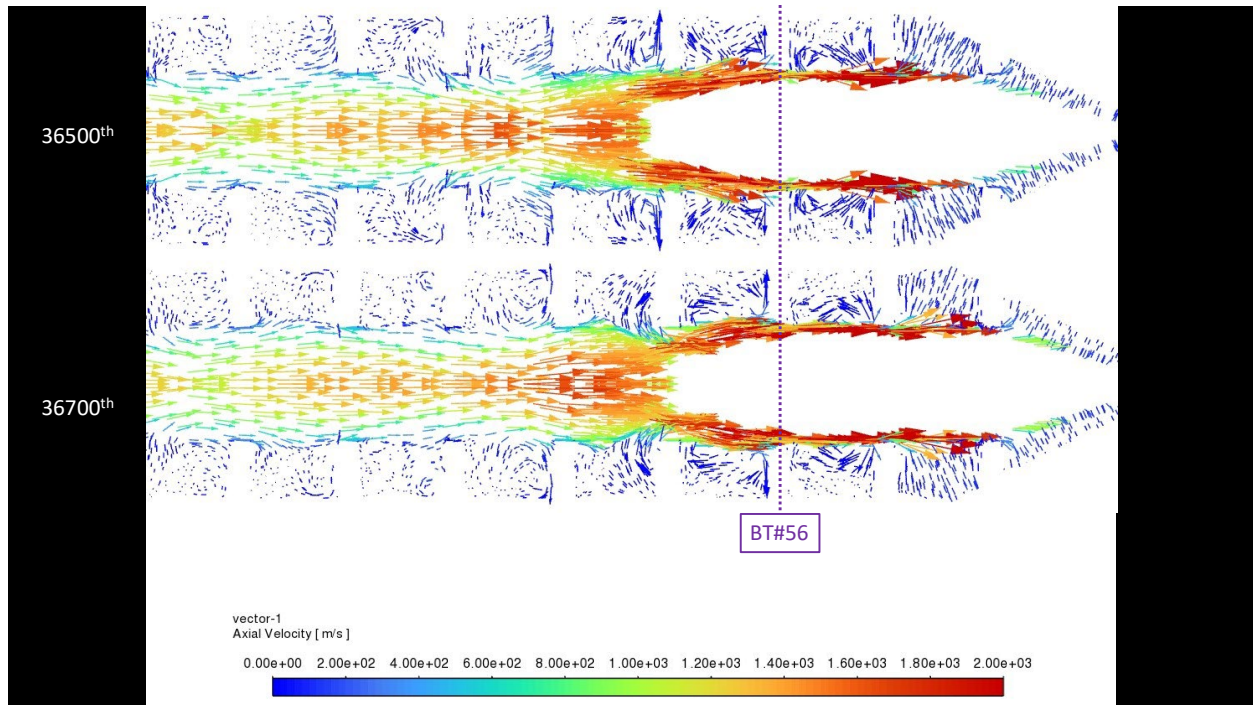


Figure 58 velocity vector field colored by magnitude of the axial velocity of P380-2B-12-15 inside BTRA111 at 1.0 km/s (36500th to 36700th time step)

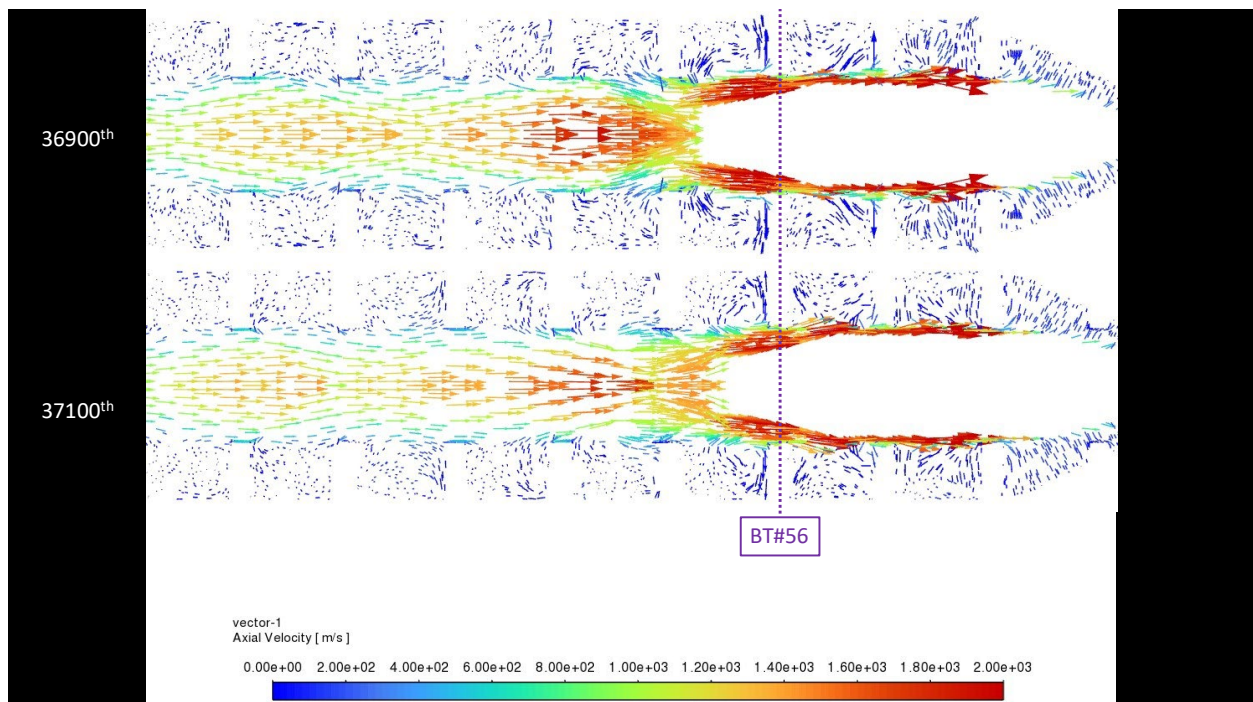


Figure 59 velocity vector field colored by magnitude of the axial velocity of P380-2B-12-15 inside BTRA111 at 1.0 km/s (36900th to 37100th time step)

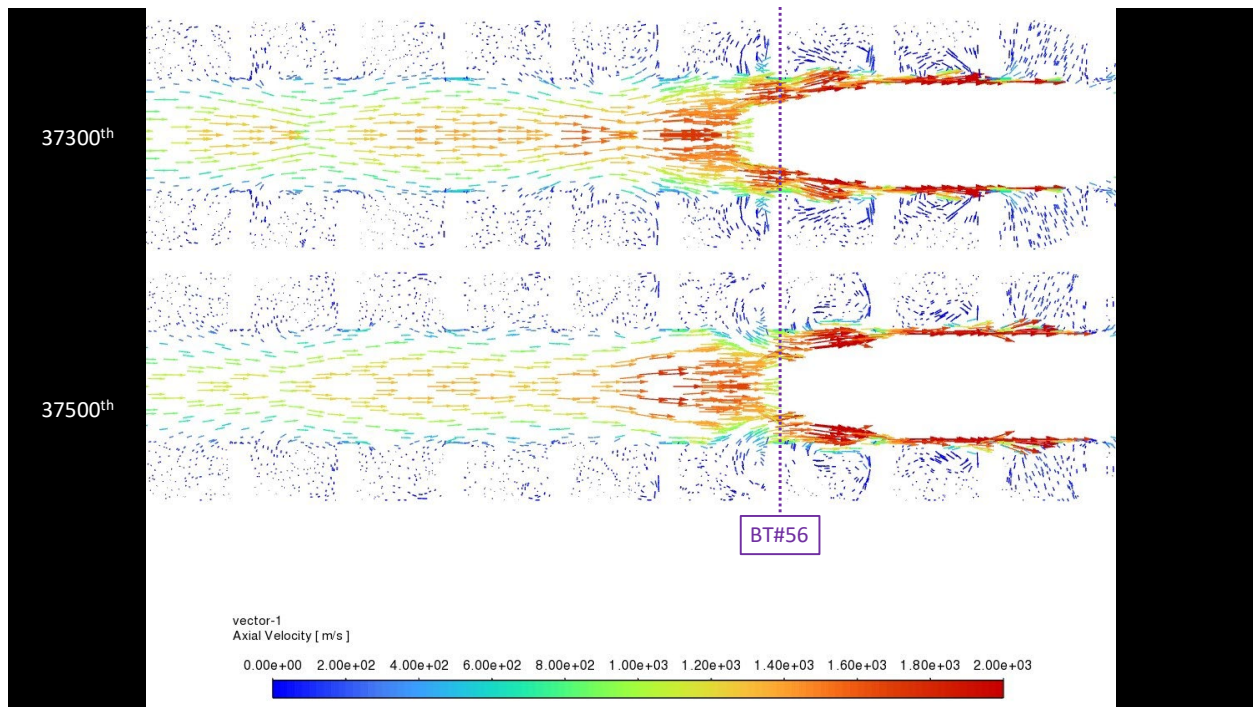


Figure 60 velocity vector field colored by magnitude of the axial velocity of P380-2B-12-15 inside BTRA111 at 1.0 km/s (37300th to 37500th time step)

Several projectiles were designed for both RTRA and BTRA configurations with different characteristics some of which require full 3-dimensional CFD simulations in order to understand their performance in BTRA and RTRA configuration. Some examples of different projectiles for RTRA and BTRA are shown in Figure 61. These projectiles were designed to manipulate the flow with the overall goal of suppressing the forward moving combustion region on the base and tail of the projectile to delay and/or prevent the projectile unstart.

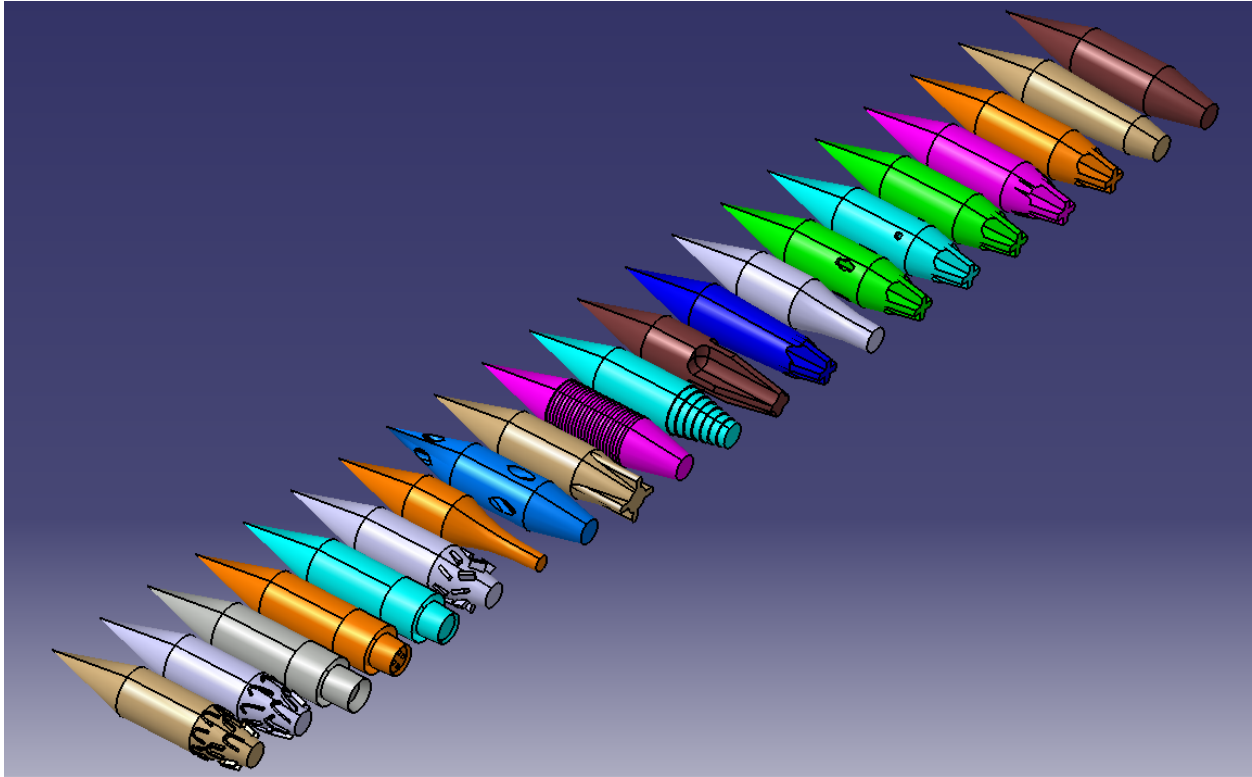


Figure 61 projectile concepts considered for RTRA and BTRA configurations

3.5 Impact of Outer-Diameter Variation of BTRA on The Performance

The CFD simulation of P380-2B-12-15 (short projectile) are conducted in various BTRA configurations at 1.0 km/s at 20.4 atm fill pressure and 300 K fill temperature inside $1\text{CH}_4+2\text{O}_2+4.67\text{N}_2$ mixture to study the effect of varying outer-diameter of the BTRA on its performance. The outer-diameter of BTRAs on these CFD cases varies from 3.0" to 2.0" as shown in Table 10. This table is identical to Table 6 in Section 3.3 (3.3 Geometries Used in CFD Modeling of BTRA, Objectives, and Test Matrices) and it is repeated here for completeness. BTRA601 with outer-diameter of 2.0" and BTRA602 with outer-diameter of 2.2" unstated very early on during the simulations. BTRA601 and BTRA602 thrust performance plots and flow fields are not documented in this report, but data exists for future revisit (stated for clarity). BTRA111-to-501 is

a hybrid CFD domain that contains BTRA111 configuration from Baffle#1 to Baffle#39 with outer-diameter of 3.0" and then switch to BTRA501 with outer-diameter of 2.5". The projectile remained started inside BTRA111, BTRA501, and BTRA111-to-501 at 1.0 km/s, but it had different performance characteristic.

Table 10 test matrix: outer-diameter variation of BTRA with the baseline projectile

	BTRA111	BTRA501	BTRA111-to-501	BTRA601	BTRA602
OD	3.0"	2.5"	3.0"-to-2.5"	2.0"	2.2"
Velocity	1.0 km/s	1.0 km/s	1.0 km/s	1.0 km/s	1.0 km/s
Status	Started	Started	Started	Unstarted	Unstarted

First, a short content associated with the non-dimensional thrust and relevant flow field maps for BTRA111, BTRA501, and BTRA111-to-501 configurations are shown. Then, their performances are compared at the end of this section. Note that for the flow field comparisons, Baffle#56 was chosen as the reference baffle to extract the flow field around this location in the laboratory frame of reference. The rationale behind choosing Baffle#56 was to pick a baffle location near end of the CFD domain where the flow may have reached the quasi-periodic solution.

3.5.1 P380-2B-12-15 in BTRA111 at 1.0 km/s

The P380-2B-12-15 projectile has a 3.0-4.0-unit non-dimensional thrust when it moves at 1.0 km/s inside BTRA111 configuration. The drag contribution from the nose cone is about -2.0-unit and relatively constant. While, the base and tail of the projectile continuously generate thrust and do not reach a quasi-periodic solution as it is shown in Figure 62. The static pressure, static

temperature, CO-mole fraction, and the axial velocity fields are shown during 36100th to 37500th time step in Figure 63, Figure 64, Figure 65, and Figure 66 accordingly.

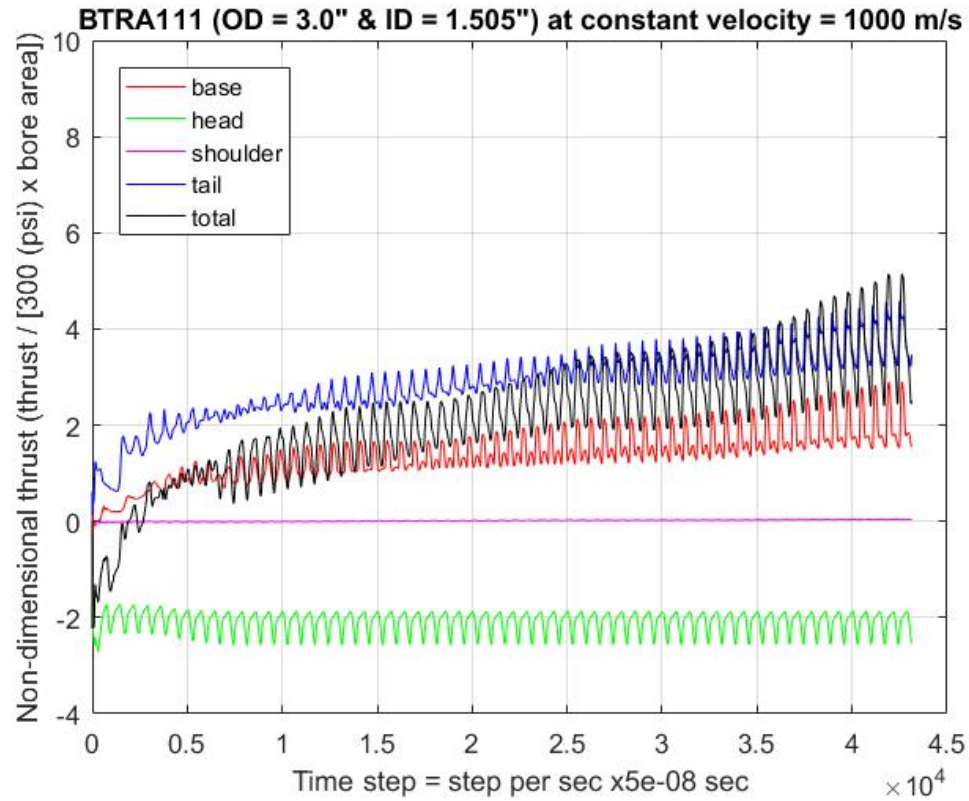


Figure 62 non-dimensional thrust breakdown of P380-2B-12-15 inside BTRA111 at 1.0 km/s

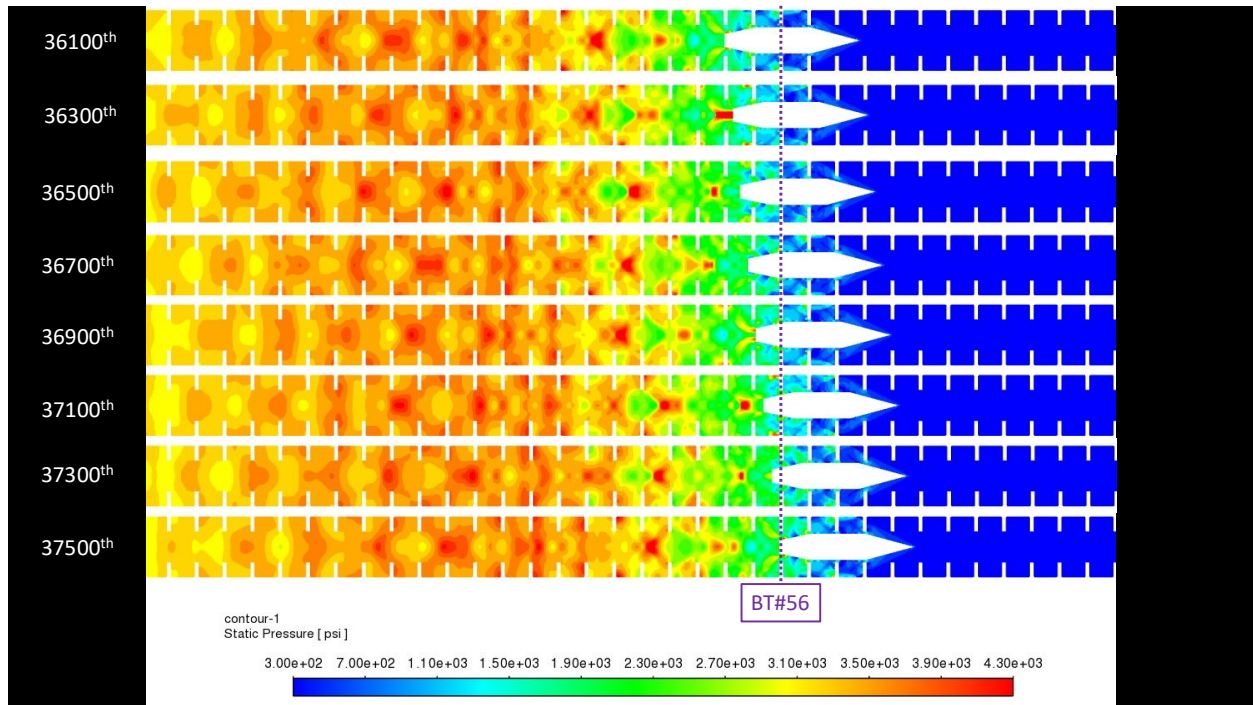


Figure 63 static pressure of P380-2B-12-15 inside BTRA111 at 1.0 km/s near Baffle#56

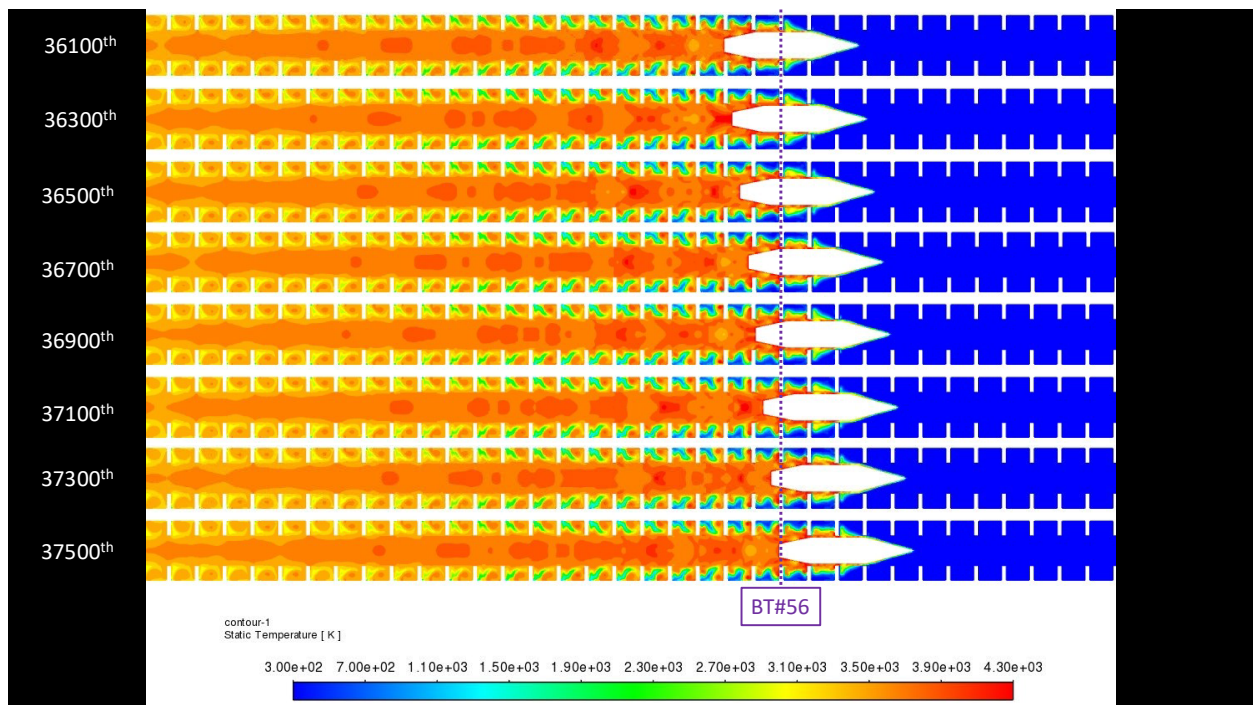


Figure 64 static temperature of P380-2B-12-15 inside BTRA111 at 1.0 km/s near Baffle#56

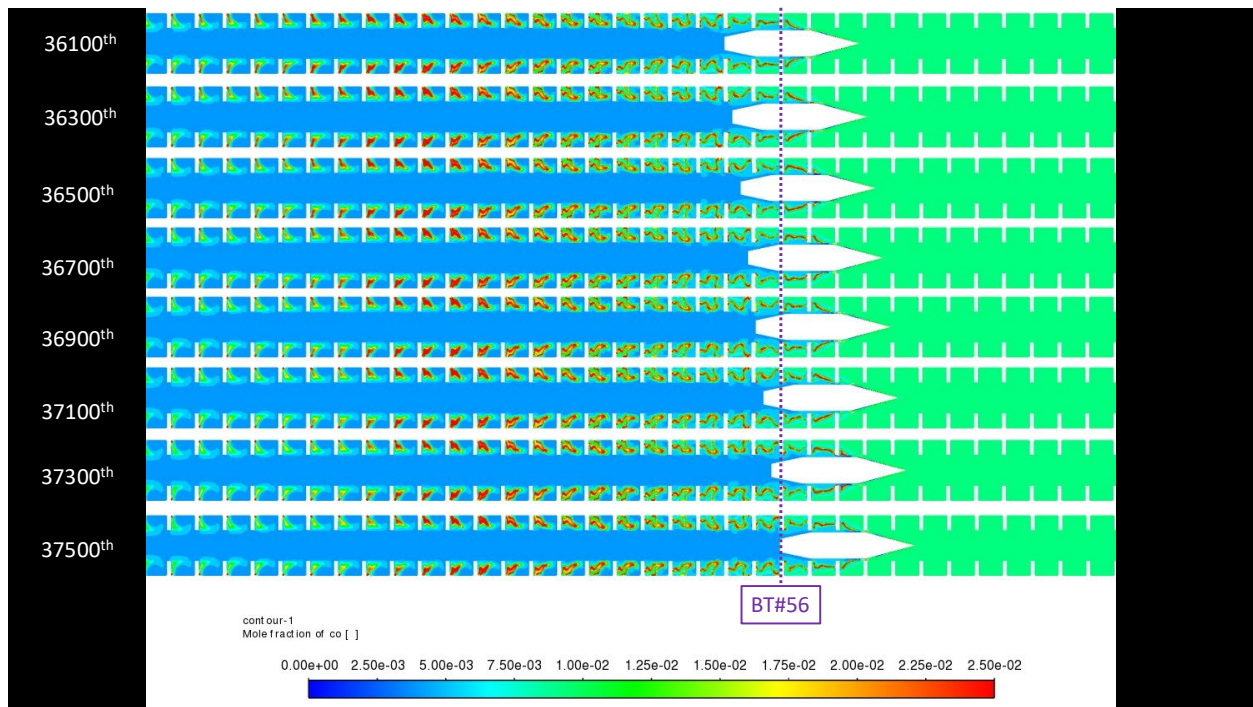


Figure 65 CO-mole fraction of P380-2B-12-15 inside BTRA111 at 1.0 km/s near Baffle#56

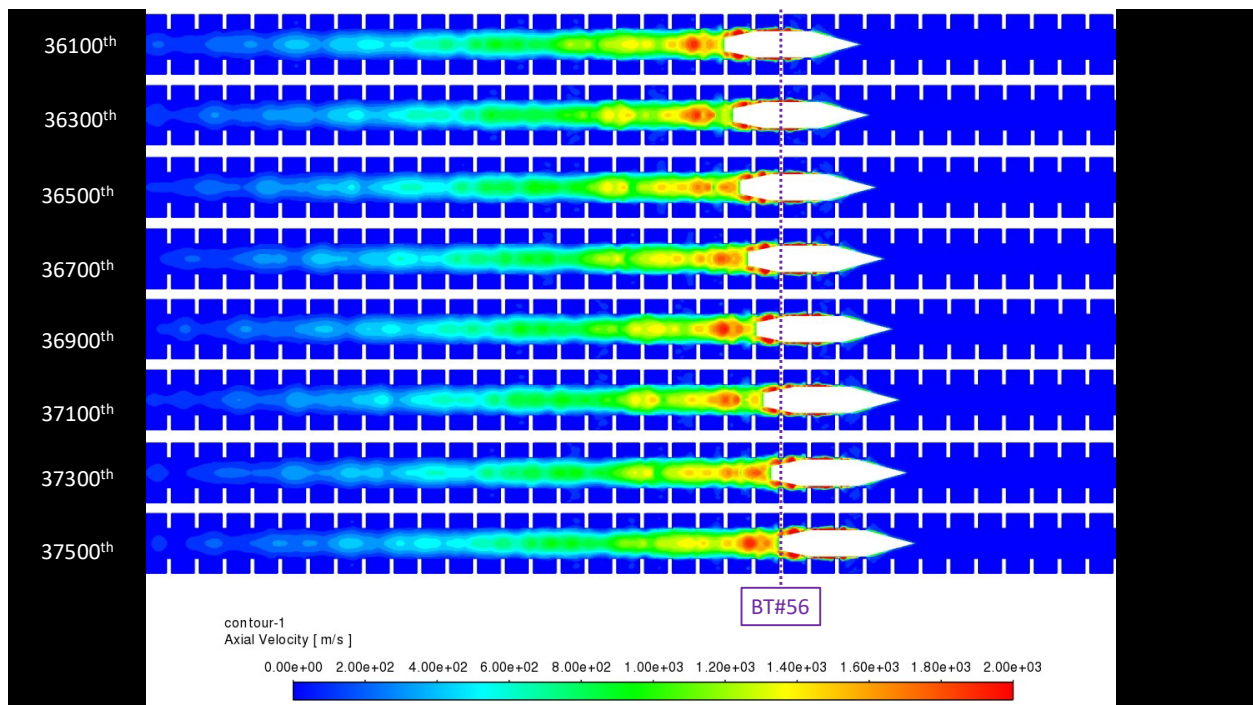


Figure 66 axial velocity of P380-2B-12-15 inside BTRA111 at 1.0 km/s near Baffle#56

3.5.2 P380-2B-12-15 in BTRA501 at 1.0 km/s

The P380-2B-12-15 projectile has a 6.8-7.0-unit non-dimensional thrust when it moves at 1.0 km/s inside BTRA111 configuration. The drag contribution from the nose cone is about -2.3-unit and relatively constant (slightly larger than of in BTRA111). While, the base and tail of the projectile continuously generate thrust and roughly reach a quasi-periodic solution at the last 20% of the CFD domain as it is shown in Figure 67. The static pressure, static temperature, CO-mole fraction, and the axial velocity fields are shown during 36100th to 37500th time step in Figure 68, Figure 69, Figure 70, and Figure 71 accordingly.

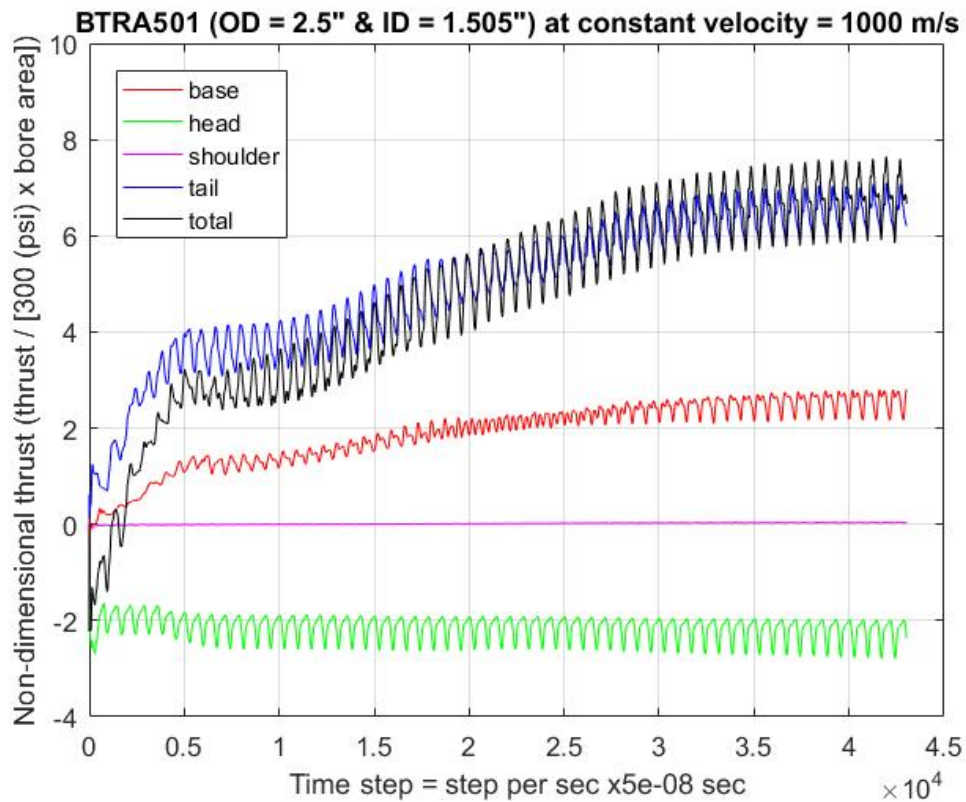


Figure 67 non-dimensional thrust breakdown of P380-2B-12-15 inside BTRA501 at 1.0 km/s

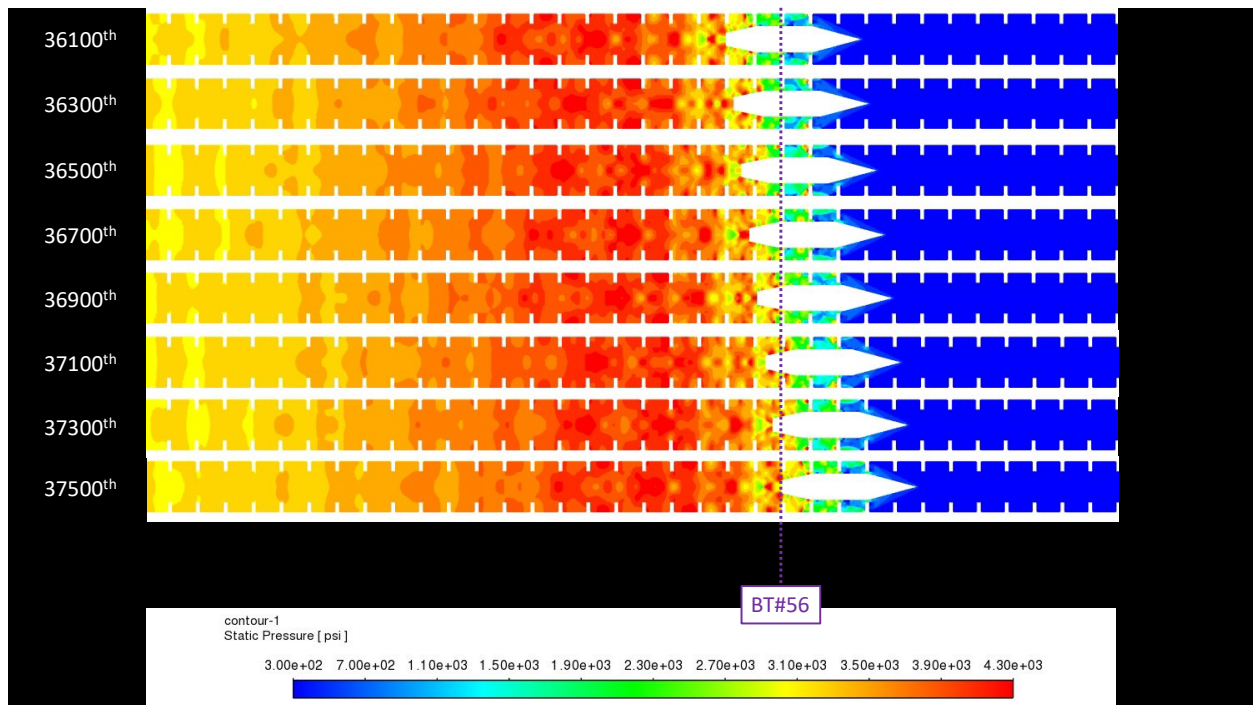


Figure 68 static pressure of P380-2B-12-15 inside BTRA501 at 1.0 km/s near Baffle#56

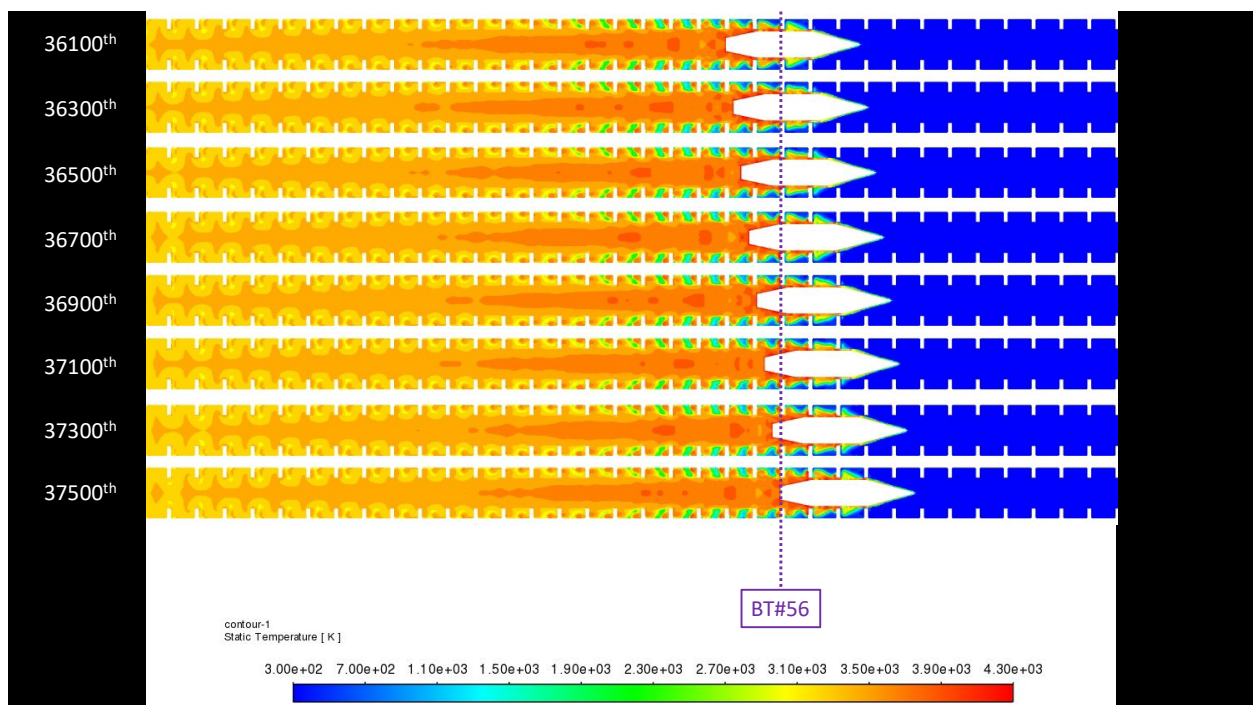


Figure 69 static temperature of P380-2B-12-15 inside BTRA501 at 1.0 km/s near Baffle#56

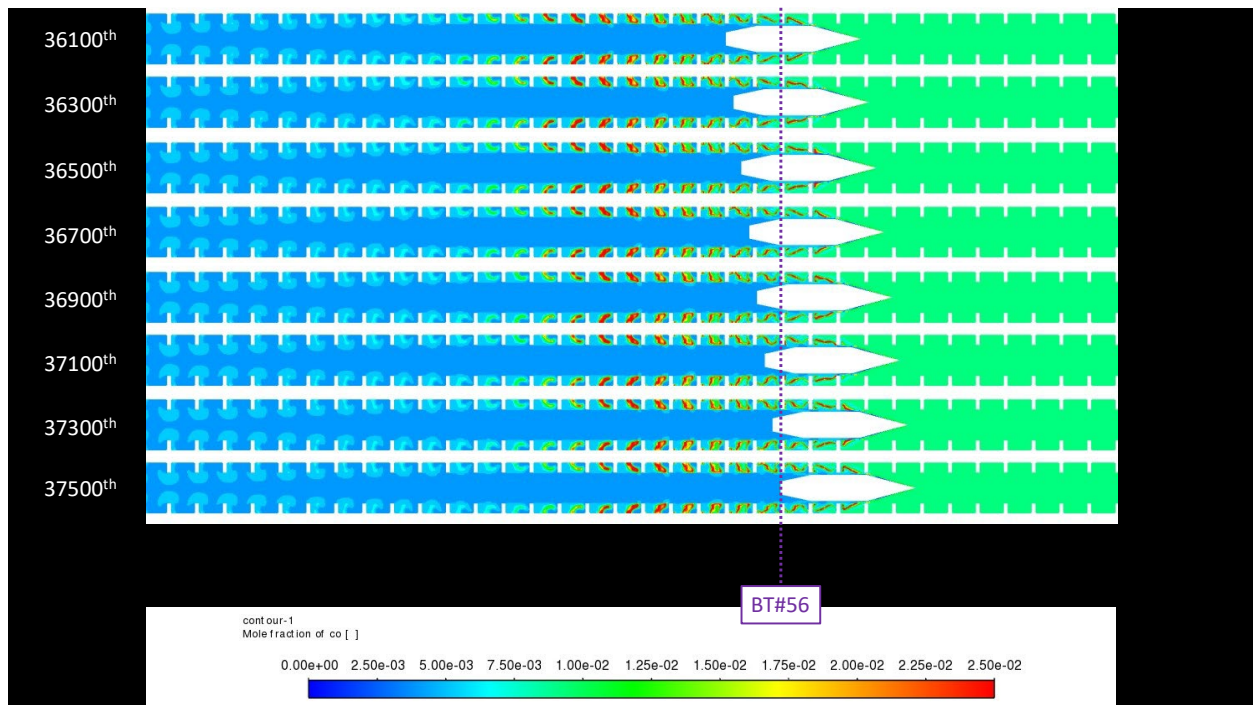


Figure 70 CO-mole fraction of P380-2B-12-15 inside BTRA501 at 1.0 km/s near Baffle#56

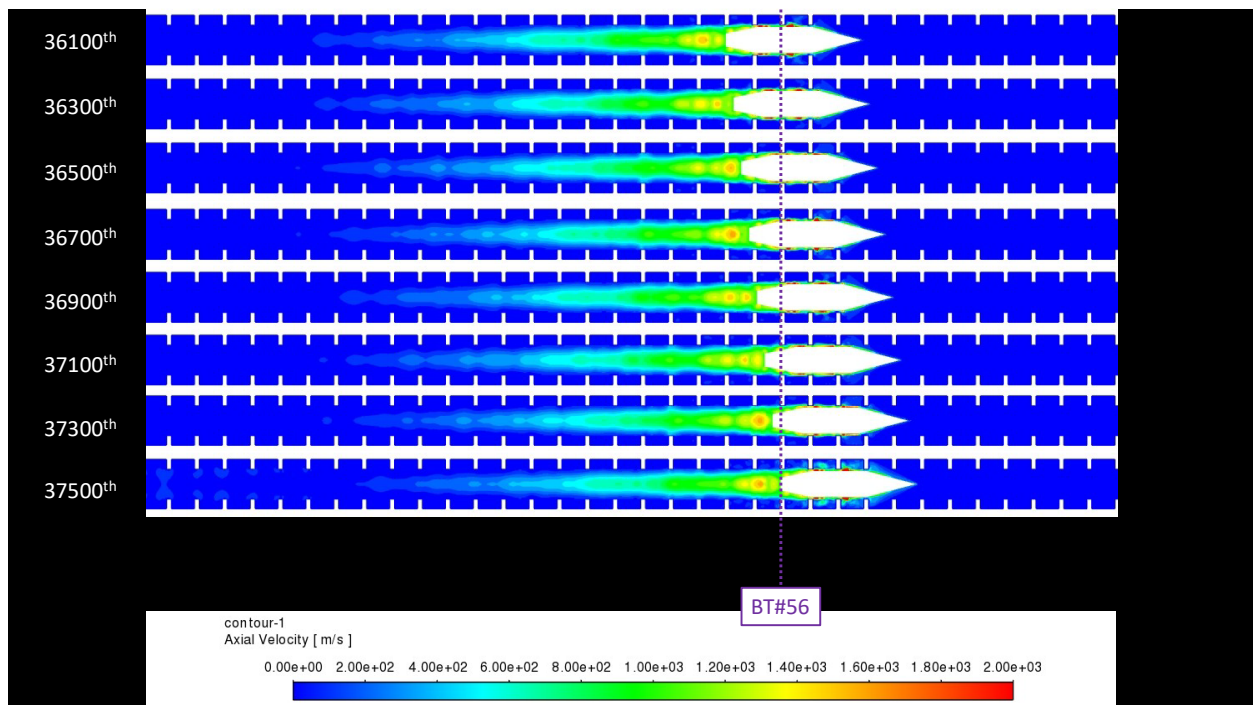


Figure 71 axial velocity of P380-2B-12-15 inside BTRA501 at 1.0 km/s near Baffle#56

3.5.3 P380-2B-12-15 in BTRA111-to-501 at 1.0 km/s

The P380-2B-12-15 projectile has a non-dimensional thrust increase from 3 to 6-unit when it moves from BTRA111 into BTRA501 configuration at 1.0 km/s. However, the thrust increase has a large fluctuation as it transitions from BTRA111 to BTRA501. Noticeably, the drag contribution from the nose cone is initially about -2.0-unit and relatively constant until the projectile moves into the BTRA501 section and it experiences an increase in drag to about -3.0-unit. This behavior might be due to the sudden volume reduction from one to the other BTRA configuration. The high energetic flow near the shoulder momentarily surges past the shoulder and reaches the nose cone region and some high-pressure pockets remain on the nose cone and increases the overall drag. The overall non-dimensional thrust increases throughout the transition; however, its non-dimensional thrust remains less than that of the thrust in the BTRA501 configuration. It is speculated that if the BTRA501 segment of this configuration were longer, the flow might have reached a quasi-periodic solution eventually, but its non-dimensional thrust would not reach 7.0-unit as it did in BTRA501. In addition to non-uniform behavior of the nose cone, the tail and base of the projectile show large thrust fluctuation after the projectile transitions into BTRA501.

The flow field examination right after the transition segment suggests that operating in BTRA111-to-501 configuration is feasible, however a gentler transition such as “sweeper” concept [37] and/or continuous transition introduce less performance fluctuations as the projectile smoothly moves from one segment to the other. A continuous transition can be conceptualized by reducing the outer-diameter of the initial BTRA section to a target BTRA section over 5-6 segments each of which is at least twice as long as the projectile length. Such concept could be investigated in future works. The non-dimensional thrust of the baseline projectile in BTRA111-

to-501 is shown in Figure 72. The static pressure, static temperature, CO-mole fraction, and the axial velocity fields are shown during 36100th to 37500th time step in Figure 73, Figure 74, Figure 75, and Figure 76 accordingly.

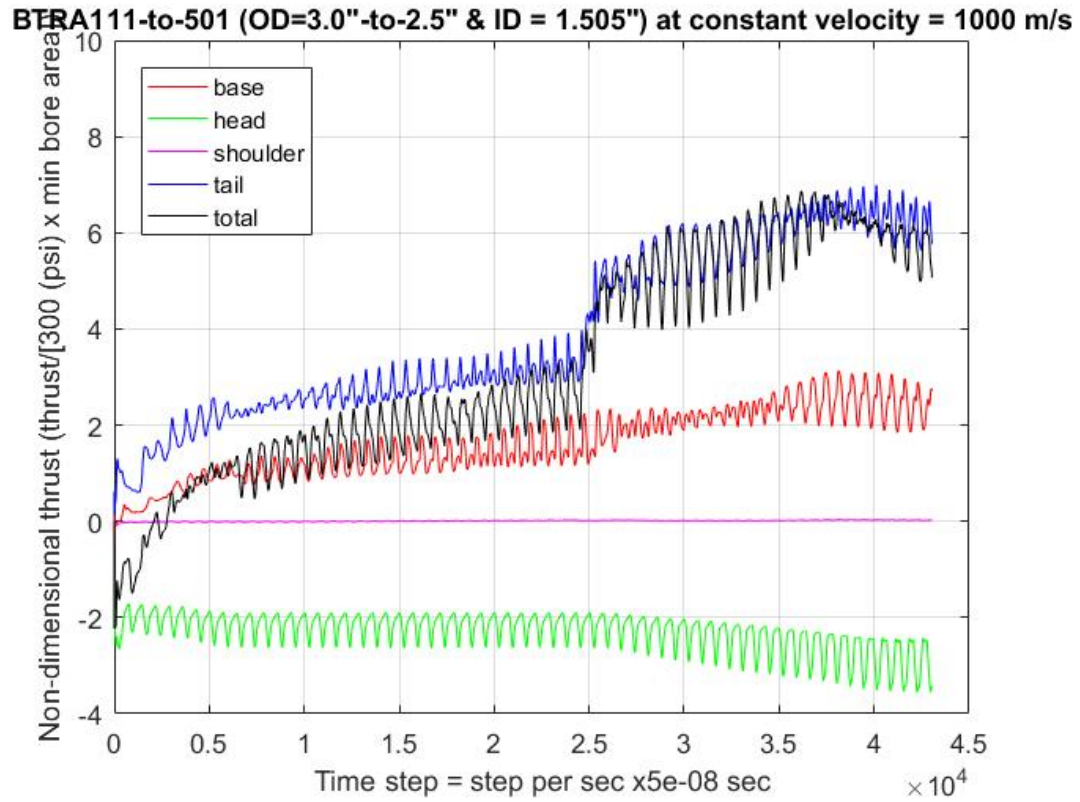


Figure 72 non-dimensional thrust breakdown of P380-2B-12-15 inside BTRA111-to-501 at 1.0 km/s

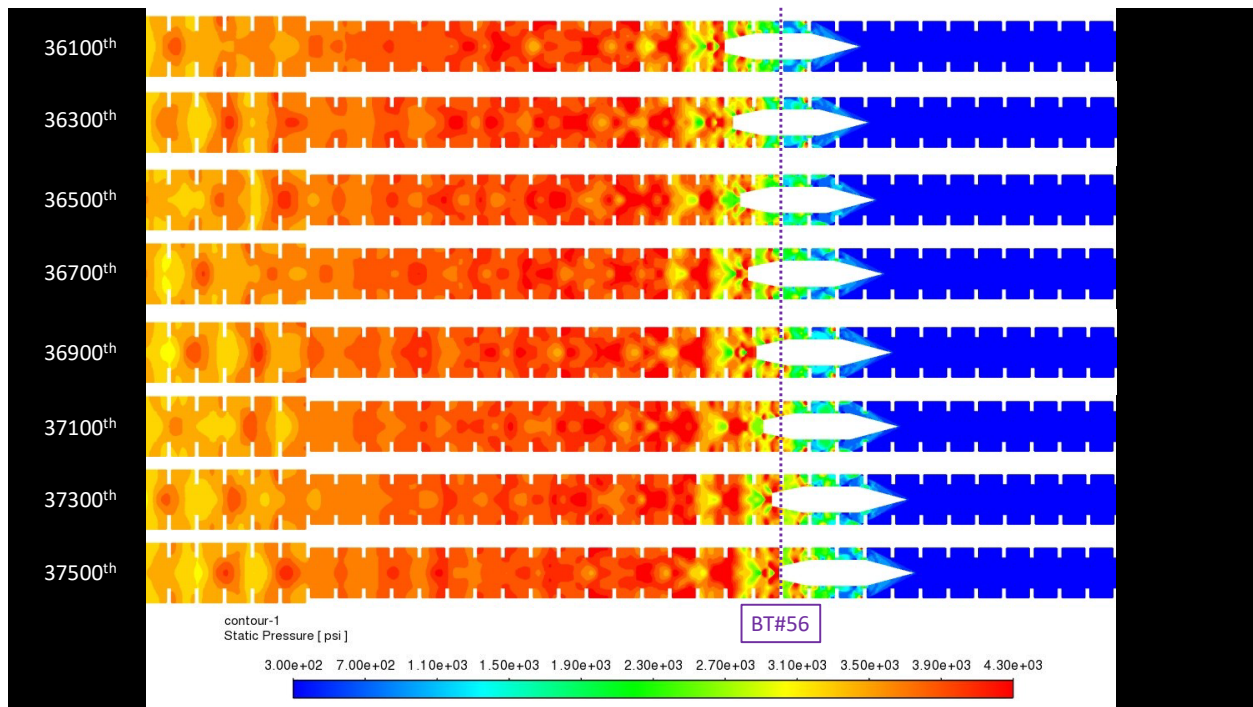


Figure 73 static pressure of P380-2B-12-15 inside BTRA111-to-501 at 1.0 km/s near Baffle#56

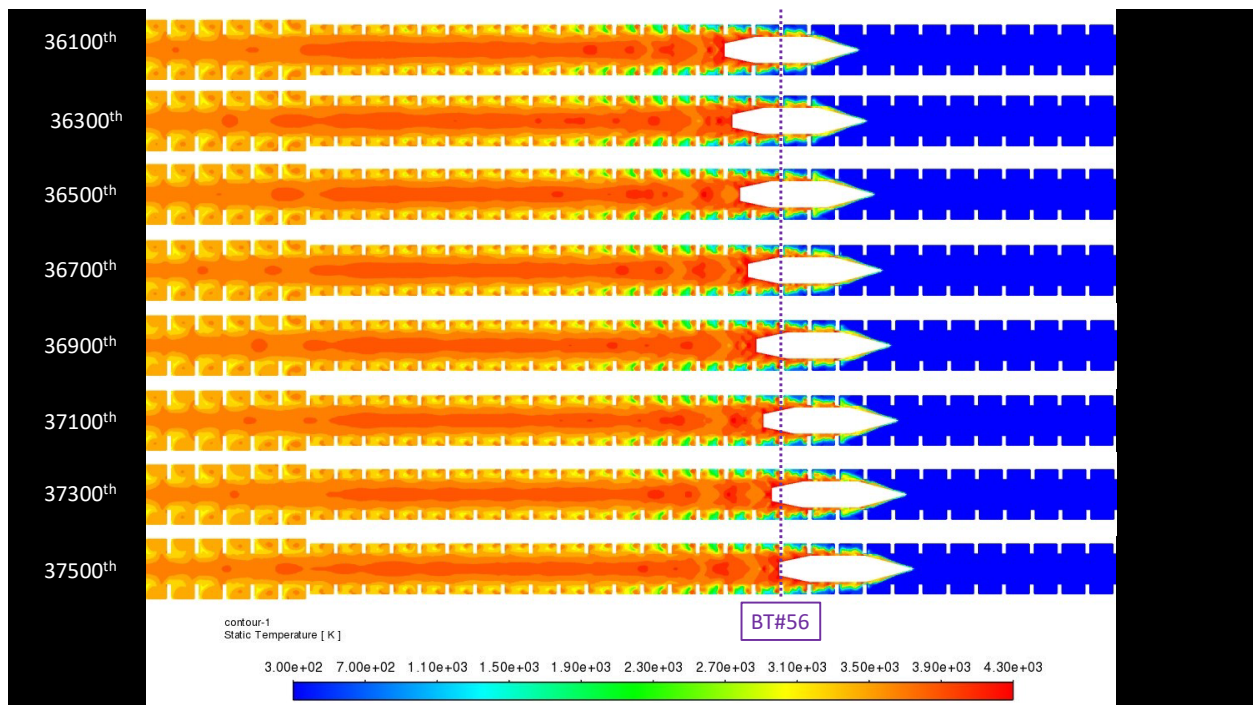


Figure 74 static temperature of P380-2B-12-15 inside BTRA111-to-501 at 1.0 km/s near Baffle#56

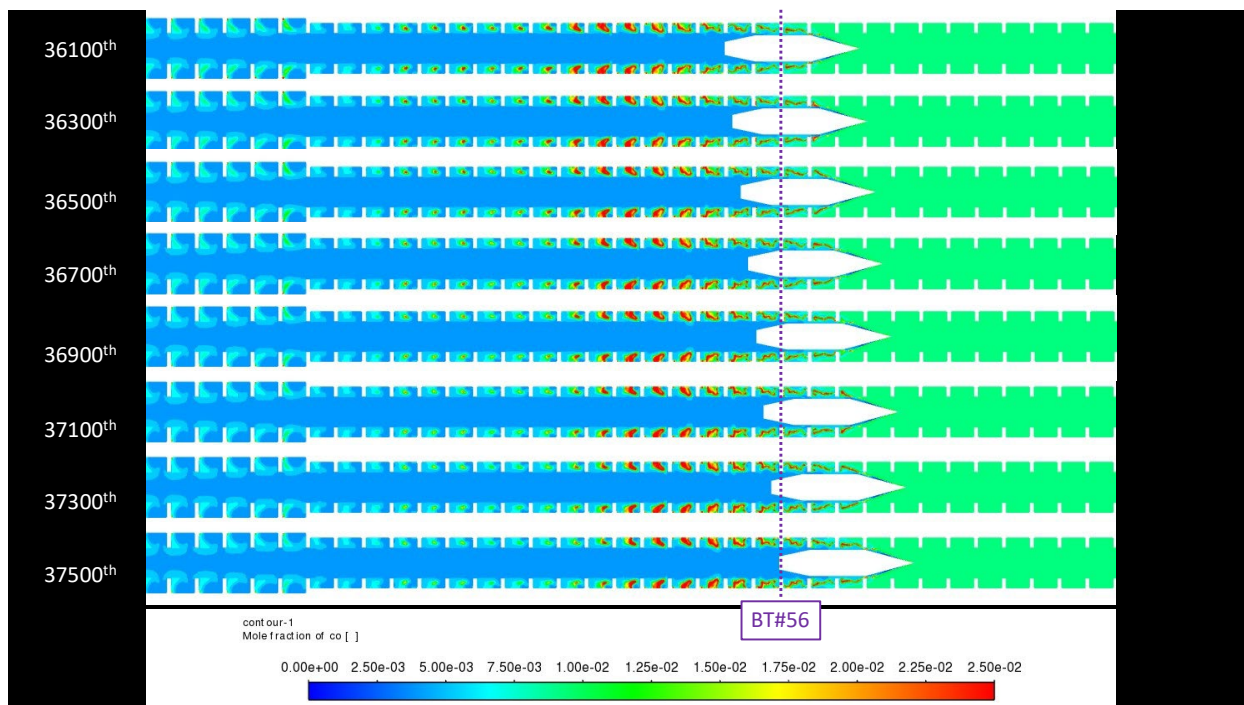


Figure 75 CO-mole fraction of P380-2B-12-15 inside BTRA111-to-501 at 1.0 km/s near Baffle#56

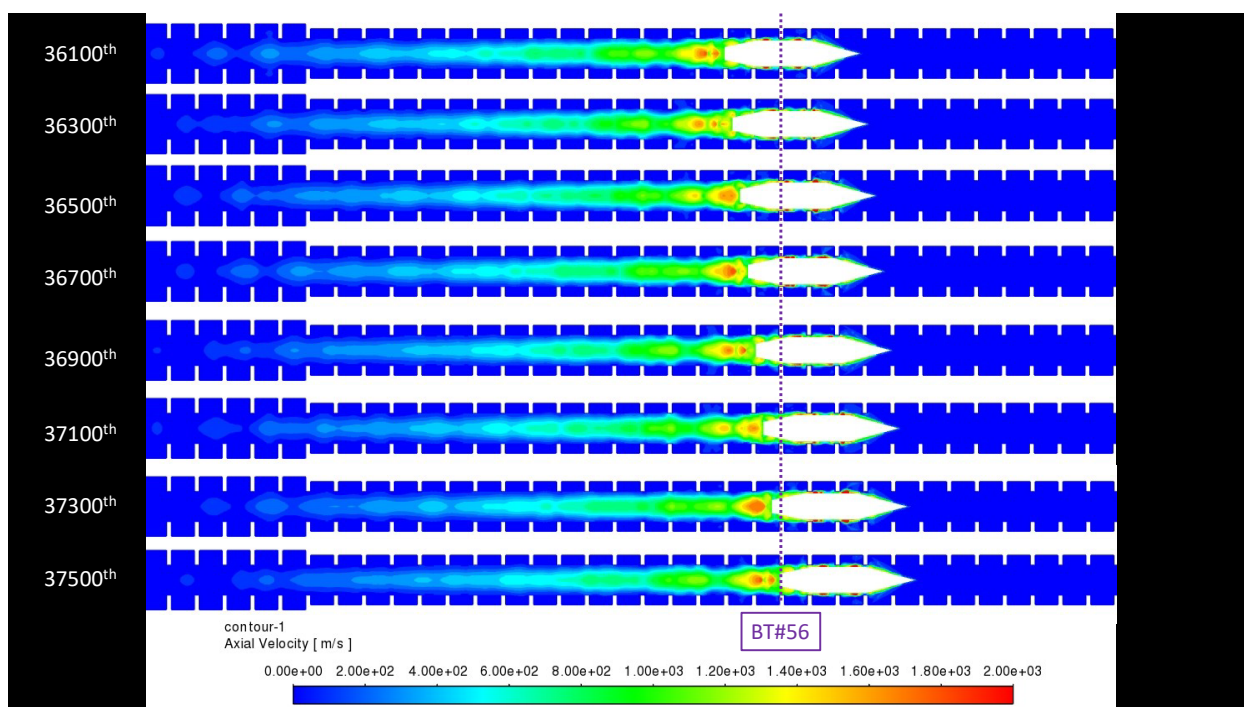


Figure 76 axial velocity of P380-2B-12-15 inside BTRA111-to-501 at 1.0 km/s near Baffle#56

3.5.4 P380-2B-12-15 in BTRA111 vs. 501 vs. 111-to-501 at 1.0 km/s Discussion

The non-dimensional thrust of P380-2B-12-15 moving at 1.0 km/s in BTRA111, BTRA501, and BTRA111-to-501 appended with the static pressure fields and CO-mole fraction are shown in Figure 77 and Figure 78 accordingly. In all three cases, the thrust contribution from the tail of projectile is larger than that of the base due to its larger projected area. Also, when maximum peak thrust on the base is realized, it coincides with minimum thrust on the tail and maximum drag force on the nose cone. Conversely, when the maximum peak thrust on the tail is realized, it coincides with minimum thrust on the base and minimum drag on the nosecone in all three cases. The nose cone only generates drag and its peak drag contribution arises every time the nose-shoulder joint passes through the hole in a baffle, which coincides with the rear edge of the two-baffle-insert-length projectile shoulder entering a baffle hole too. The net thrust reaches a quasi-periodic state only on BTRA501 at latter part of the simulations. In general, a quasi-periodic non-dimensional thrust indicates that combustion driven shockwave system has stabilized into an oscillatory cycle. The instantaneous static pressure and CO-mole fraction fields start showing periodic features with less variations only in BTRA501 configuration. In general, the high-pressure region is located behind the base in BTRA501 and BTRA111-to-501 configurations. Whereas, there is some gap between the high-pressure region in BTRA111 relative to the base of the projectile which indicate why the non-dimensional thrust is lower relative to BTRA501. The CO-mole fraction field comparison shows that large amount of CO is created and consumed close to the base of the projectile in BTRA501 and BTRA111-to-501. While, larger trace of CO remains further downstream in BTRA111 that shows less efficient combustion and heat release in this configuration.

P380-2B-12-15 (short projectile) non-dimensional thrust and static pressure flow field at 1000 m/s
BTRA111(Left) vs. BTRA501(Center) vs. BTRA111-to-501 (Right)

Flow field evolution shown below collected at latter part of simulation indicated by purple arrow

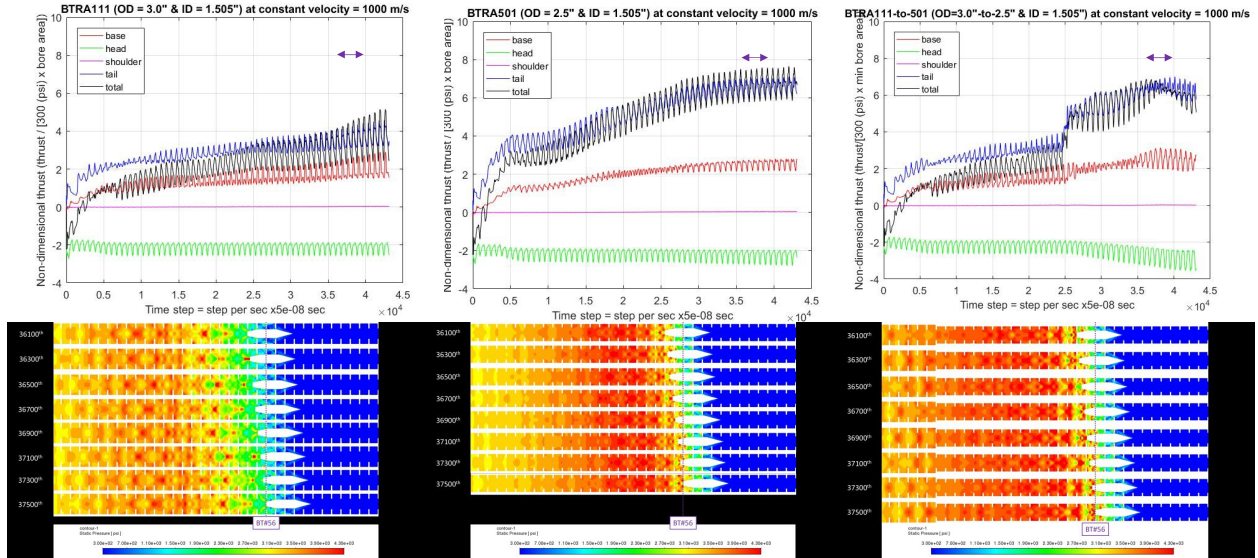


Figure 77 P380-2B-12-15 at 1.0 km/s and static pressure field inside BTRA111 vs. BTRA501 vs. BTRA111-to-501

P380-2B-12-15 (short projectile) non-dimensional thrust and CO-mole fraction flow field at 1000 m/s
BTRA111(Left) vs. BTRA501(Center) vs. BTRA111-to-501 (Right)

Flow field evolution shown below collected at latter part of simulation indicated by purple arrow

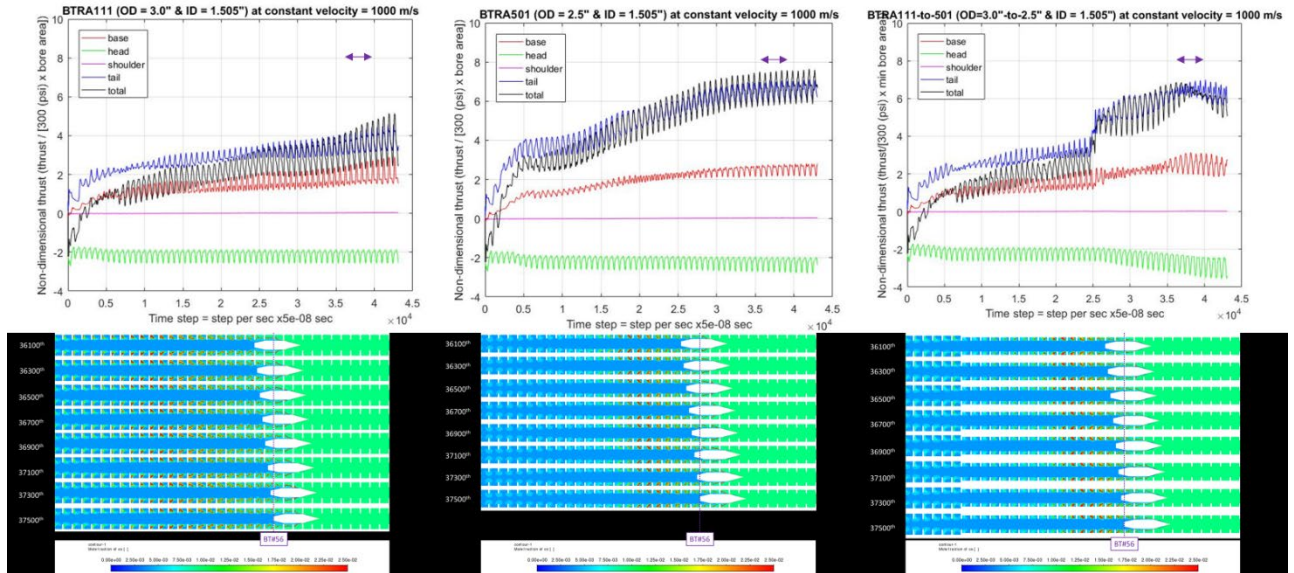


Figure 78 P380-2B-12-15 at 1.0 km/s and CO-mole fraction field inside BTRA111 vs. BTRA501 vs. BTRA111-to-501

3.6 Impact of Velocity Variation on Non-Dimensional Thrust

The CFD simulation of P380-2B-12-15 (short projectile) are conducted in BTRA501 configuration at 1.0, 1.1, 1.2, and 1.4 km/s at 20.4 atm fill pressure and 300 K fill temperature inside $1\text{CH}_4+2\text{O}_2+4.67\text{N}_2$ mixture. Also, two CFD simulation are conducted with P380-3B-12-15 (long projectile) in BTRA501 at 1.0 and 1.2 km/s with similar fill pressure and fill temperature in the same mixture. The purpose of these simulations is to identify the impact of velocity variations on the thrust performance in the same BTRA501 configuration with outer-diameter of 2.5" as it is listed in Table 11. This table is identical to Table 7 in Section 3.3 (3.3 Geometries Used in CFD Modeling of BTRA, Objectives, and Test Matrices) and it is repeated here for completeness. The short projectile remains started in all cases. Whereas, the long projectile unstarts when it moves at 1.0 km/s, but it remains started at 1.2 km/s. When the short projectile moves at constant velocity of 1.0, 1.1, 1.2, and 1.4 km/s inside BTRA501, it roughly has a 7.0, 5.0, 4.0, and 2.5-unit non-dimensional thrust accordingly. While, when the long projectile moves at a constant velocity of 1.0 and 1.2 km/s, it roughly has 3.0 and 5.0-unite non-dimensional thrust respectively. The low non-dimensional thrust of 3.0-unit at 1.0 km/s is due to the projectile unstart. More context is provided for this unstarted case in latter subsection.

Table 11 test matrix: velocity variation impact on baseline and alternative projectile in BTRA501 configuration

	1.0 km/s	1.1 km/s	1.2 km/s	1.4 km/s
Baseline Projectile	Started	Started	Started	Started
Alternative Projectile	Unstarted	-----	Started	-----

a short content associated with the non-dimensional thrust and relevant flow field maps for these 6 cases are shown in the subsequent sections. Then, their performances are compared at the end of this section. Similar to Section 3.5 (3.5 Impact of Outer-Diameter Variation of BTRA on The Performance), Baffle#56 was chosen as the reference baffle to extract the flow field around this location in the laboratory frame of reference. The rationale behind choosing Baffle#56 was to pick a baffle location near end of the CFD domain where the flow may have reached the quasi-periodic solution.

3.6.1 P380-2B-12-15 in BTRA501 at 1.0 km/s

The content of this subsection is identical to 3.5.2 and repeated for completeness of this section. The P380-2B-12-15 projectile has a 6.8-7.0-unit non-dimensional thrust when it moves at 1.0 km/s inside BTRA501 configuration. The drag contribution from the nose cone is about - 2.3- unit and relatively constant. While, the base and tail of the projectile continuously generate thrust and roughly reaches a quasi-periodic solution at the last 20% of the CFD domain as it is shown in Figure 79. The static pressure, static temperature, CO-mole fraction, and the axial velocity fields are shown during 36100th to 37500th time step in Figure 80, Figure 81, Figure 82, and Figure 83 accordingly.

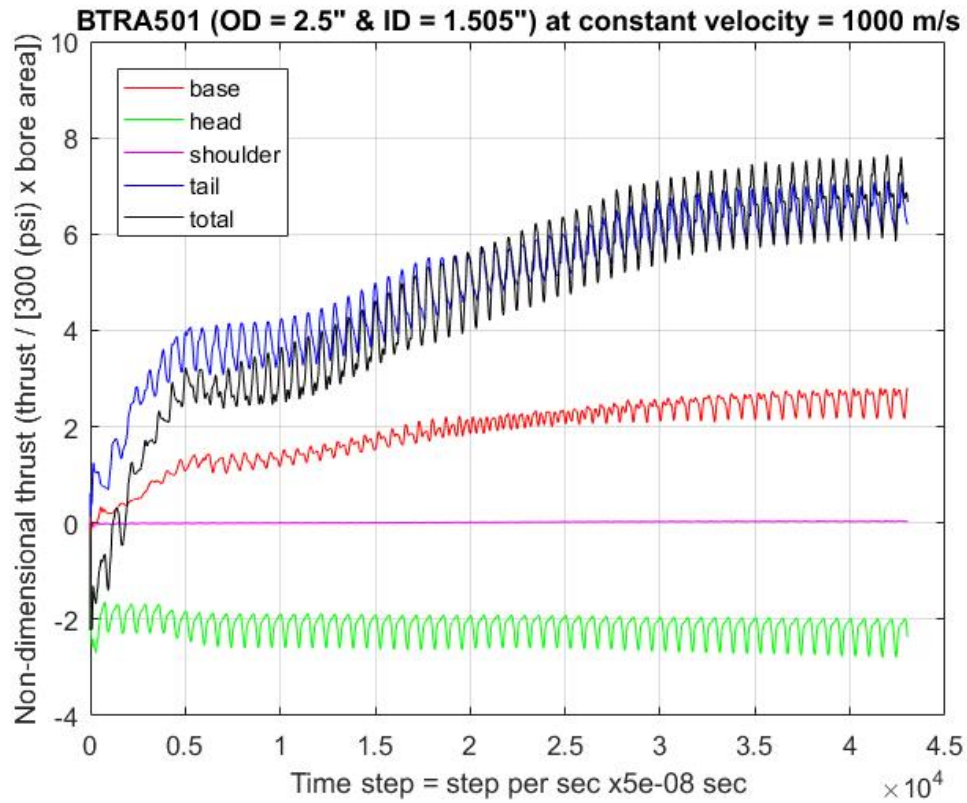


Figure 79 non-dimensional thrust breakdown of P380-2B-12-15 inside BTRA501 at 1.0 km/s

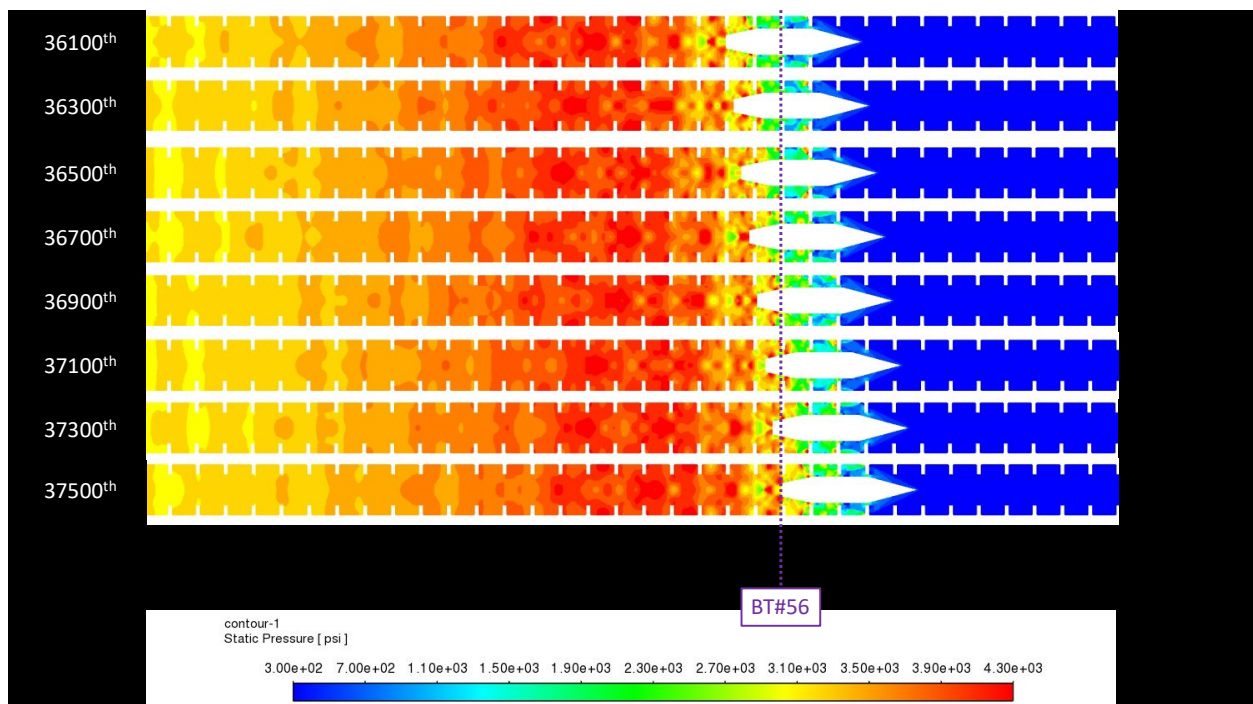


Figure 80 static pressure of P380-2B-12-15 inside BTRA501 at 1.0 km/s near Baffle#56

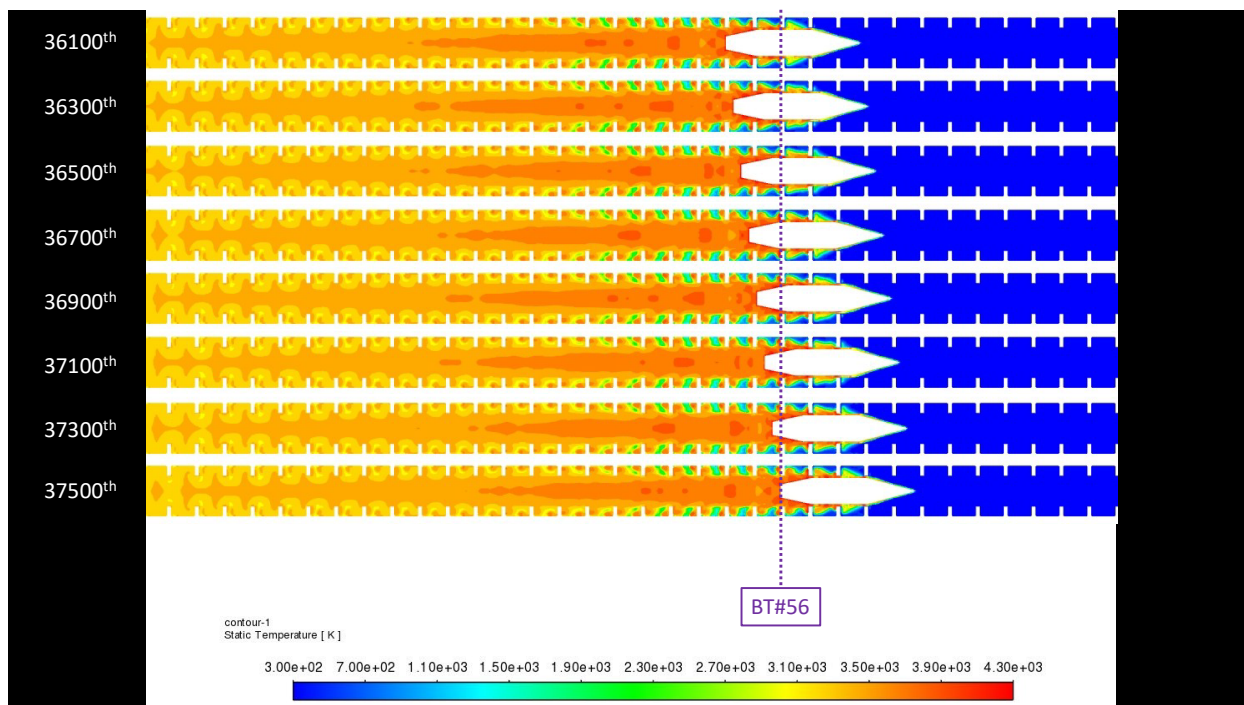


Figure 81 static temperature of P380-2B-12-15 inside BTRA501 at 1.0 km/s near Baffle#56

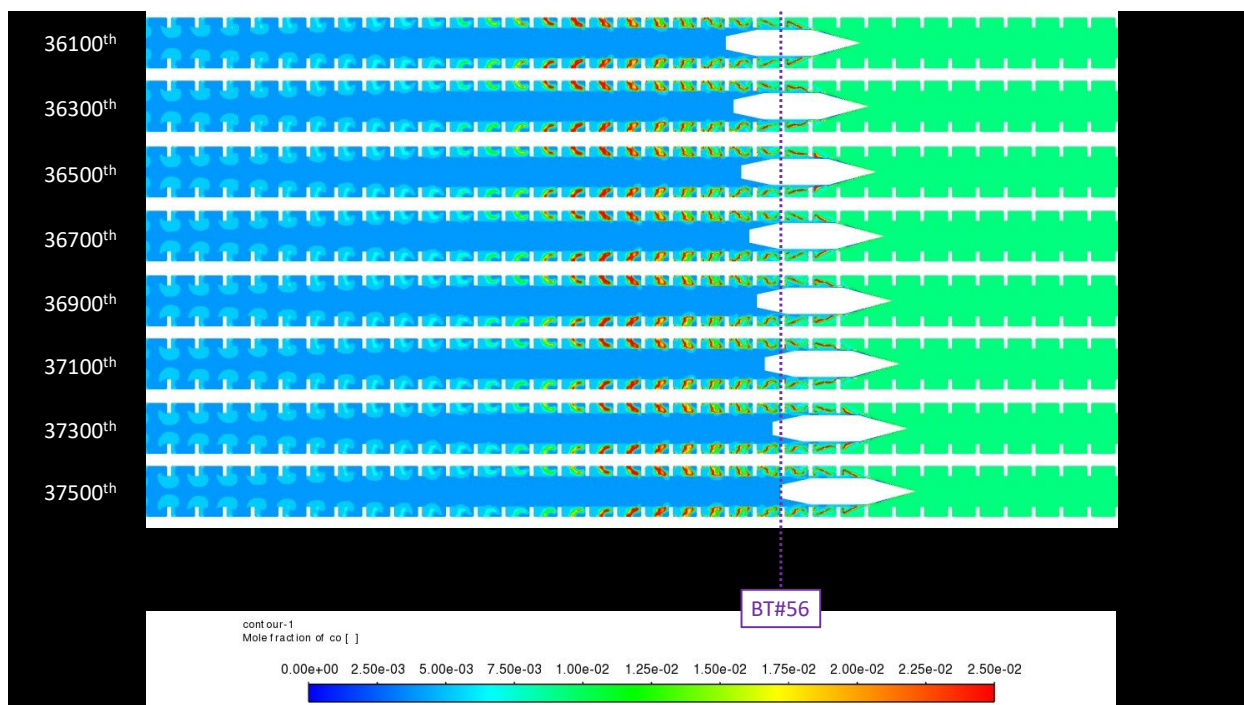


Figure 82 CO-mole fraction of P380-2B-12-15 inside BTRA501 at 1.0 km/s near Baffle#56

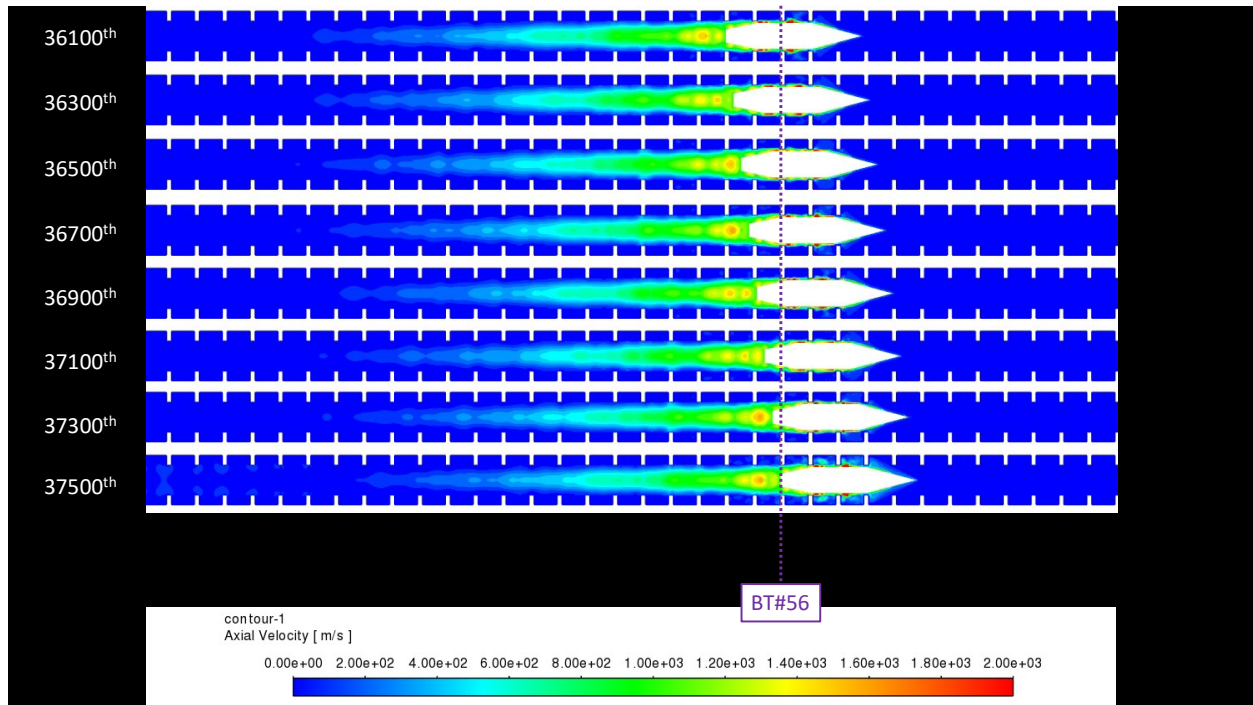


Figure 83 axial velocity of P380-2B-12-15 inside BTRA501 at 1.0 km/s near Baffle#56

3.6.2 P380-2B-12-15 in BTRA501 at 1.1 km/s

The P380-2B-12-15 projectile has a 5.0-unit non-dimensional thrust when it moves at 1.1 km/s inside BTRA501 configuration. The drag contribution from the nose cone is about -2.4-unit and relatively constant. While, the base and tail of the projectile continuously generate thrust and roughly reaches a quasi-periodic solution at the last 20-30% of the CFD domain as it is shown in Figure 84. The static pressure, static temperature, CO-mole fraction, and the axial velocity fields are shown during 36400th to 37800th time step in Figure 85, Figure 86, Figure 87, and Figure 88 accordingly.

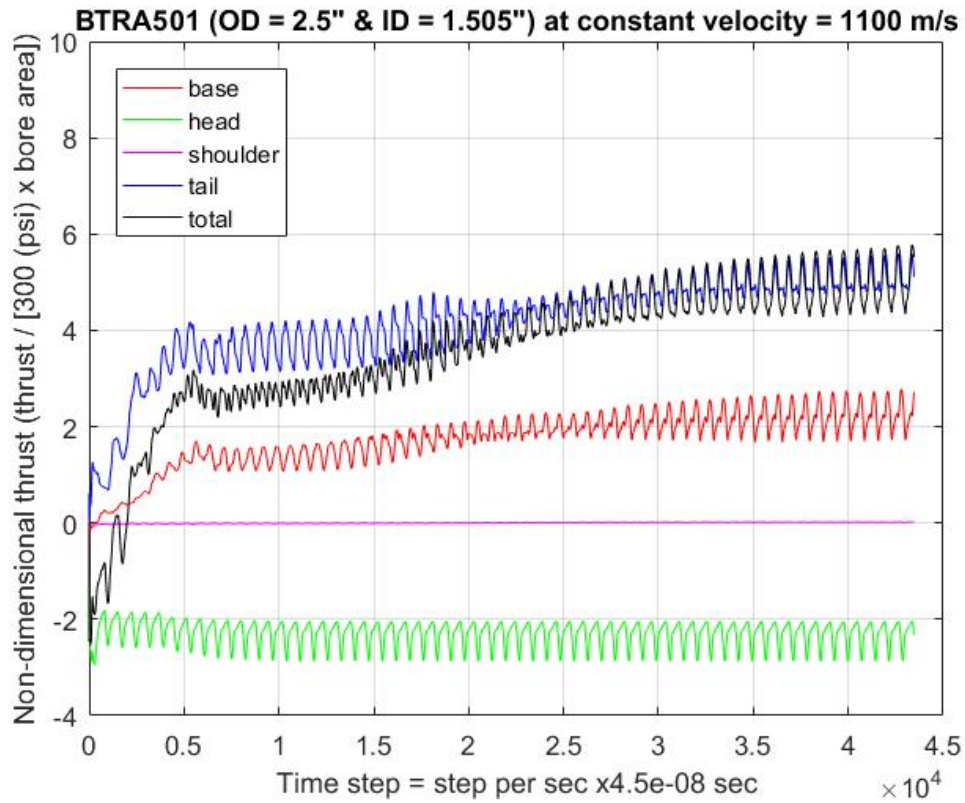


Figure 84 non-dimensional thrust breakdown of P380-2B-12-15 inside BTRA501 at 1.1 km/s

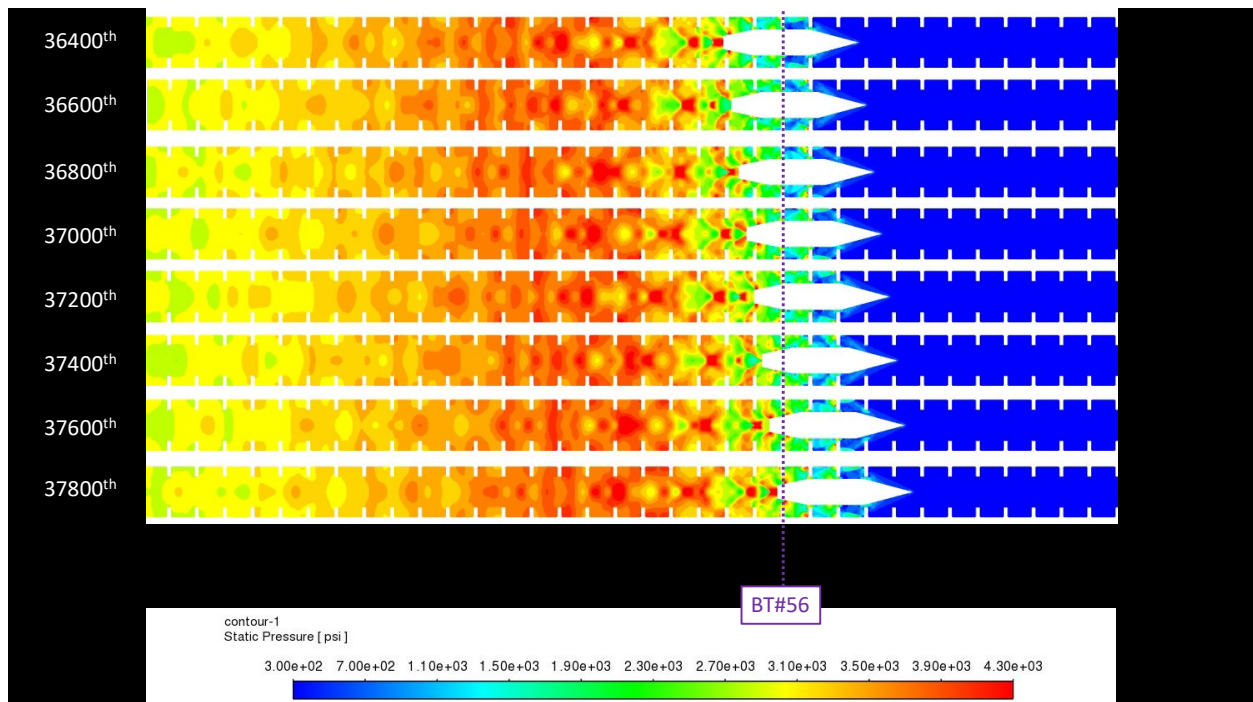


Figure 85 static pressure of P380-2B-12-15 inside BTRA501 at 1.1 km/s near Baffle#56

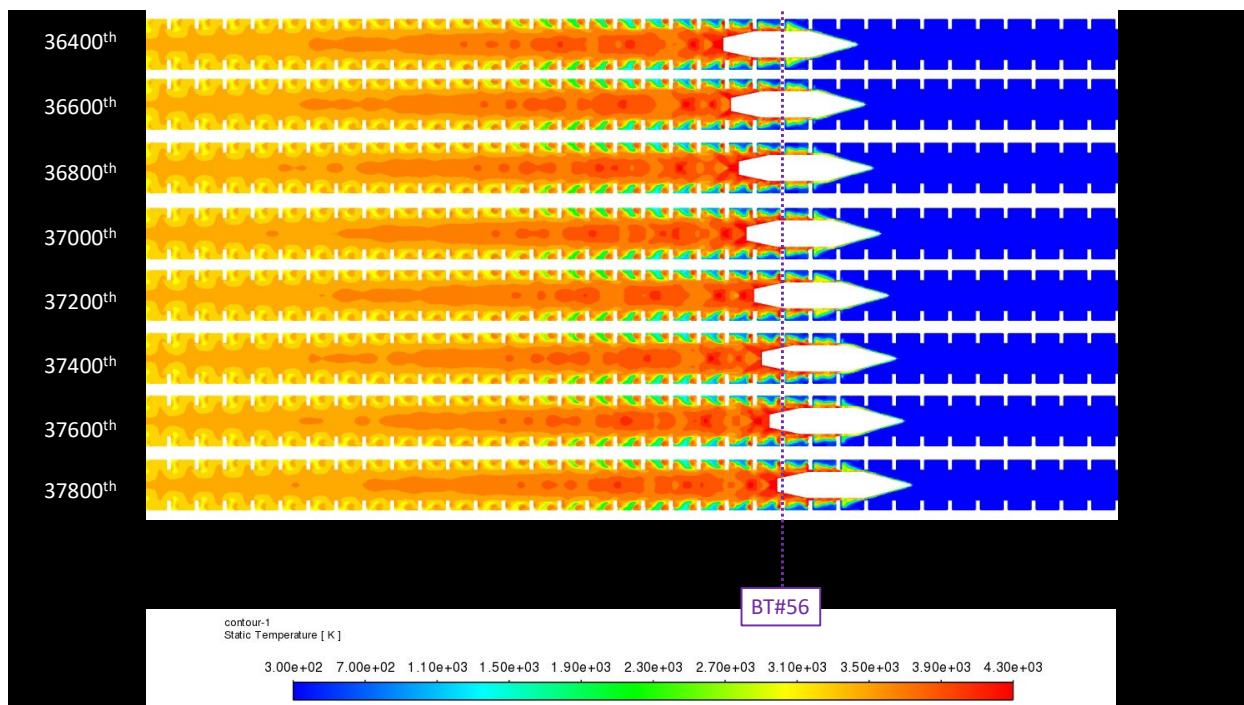


Figure 86 static temperature of P380-2B-12-15 inside BTRA501 at 1.1 km/s near Baffle#56

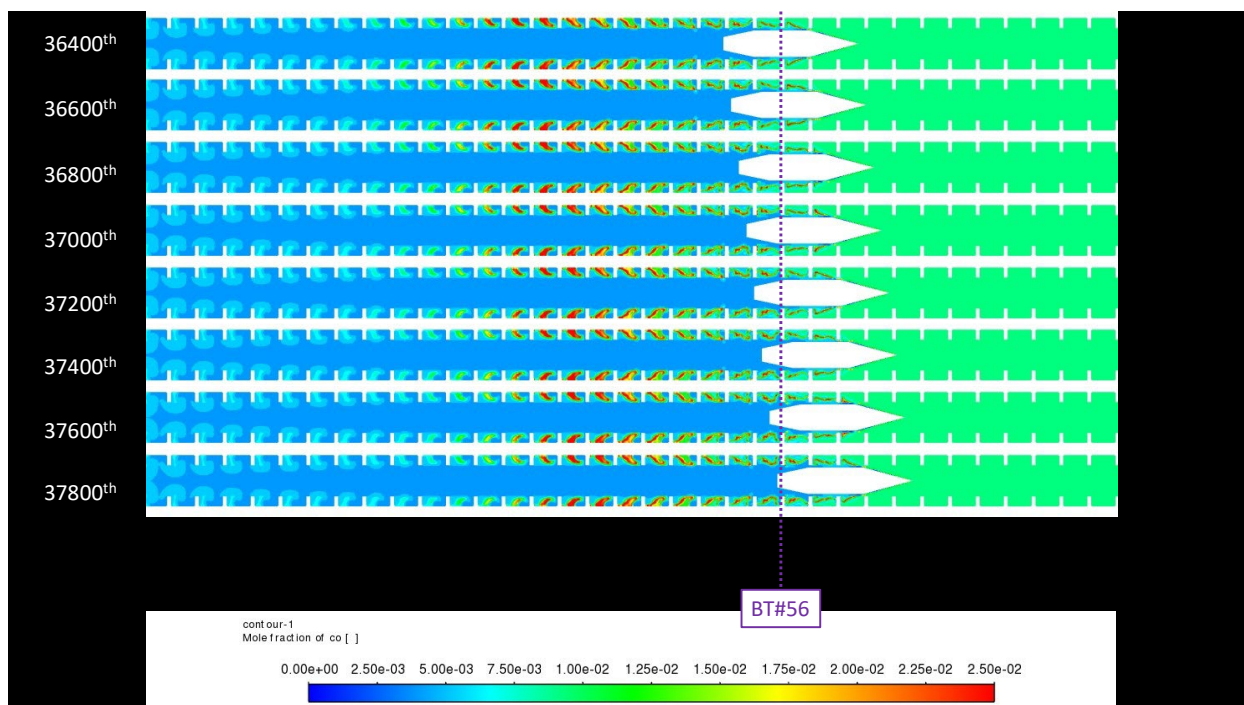


Figure 87 CO-mole fraction of P380-2B-12-15 inside BTRA501 at 1.1 km/s near Baffle#56

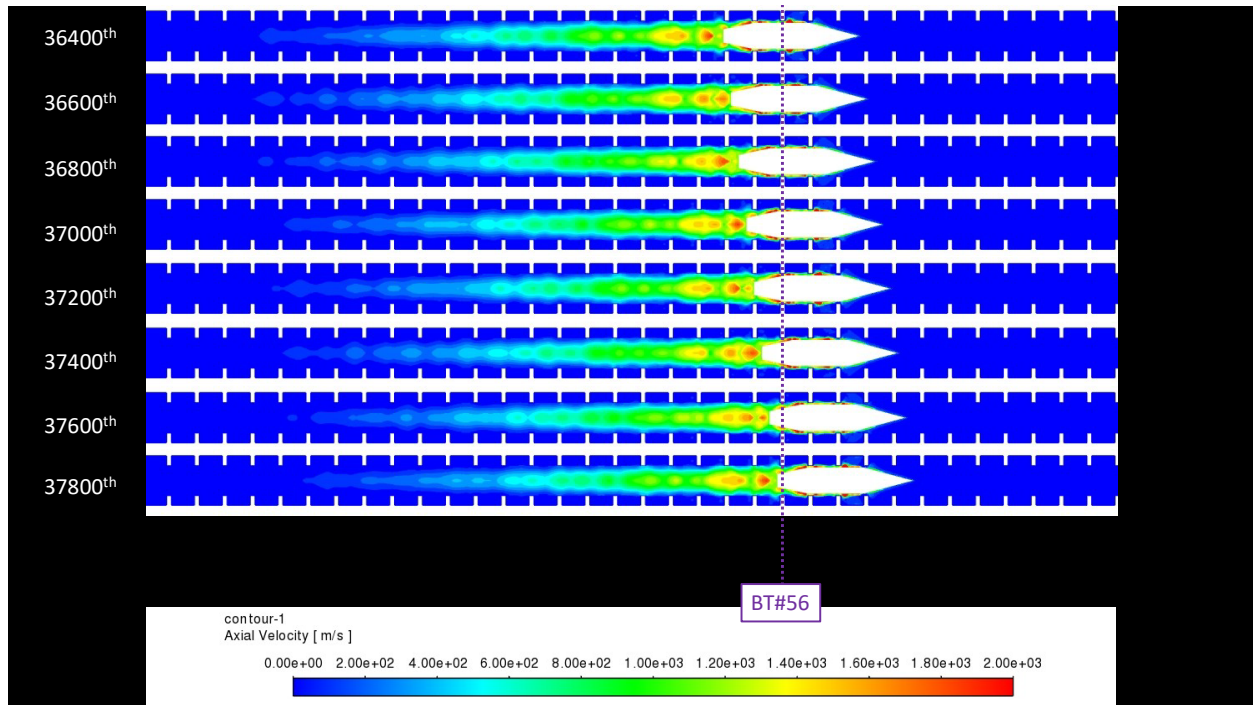


Figure 88 axial velocity of P380-2B-12-15 inside BTRA501 at 1.1 km/s near Baffle#56

3.6.3 P380-2B-12-15 in BTRA501 at 1.2 km/s

The P380-2B-12-15 projectile has a 4.0-unit non-dimensional thrust when it moves at 1.2 km/s inside BTRA501 configuration. The drag contribution from the nose cone is about -3.0-unit and relatively constant. While, the base and tail of the projectile continuously generate thrust and roughly reaches a quasi-periodic solution at the last 20-30% of the CFD domain as it is shown in Figure 89. The static pressure, static temperature, CO-mole fraction, and the axial velocity fields are shown during 36400th to 37800th time step in Figure 90, Figure 91, Figure 92, and Figure 93 accordingly.

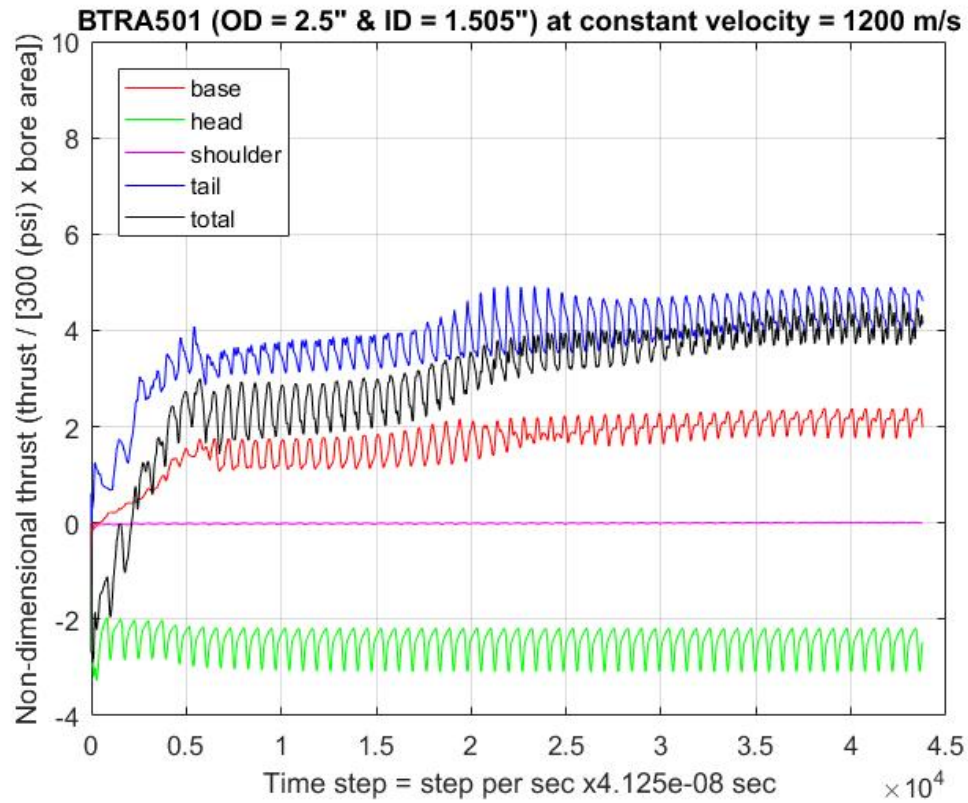


Figure 89 non-dimensional thrust breakdown of P380-2B-12-15 inside BTRA501 at 1.2 km/s

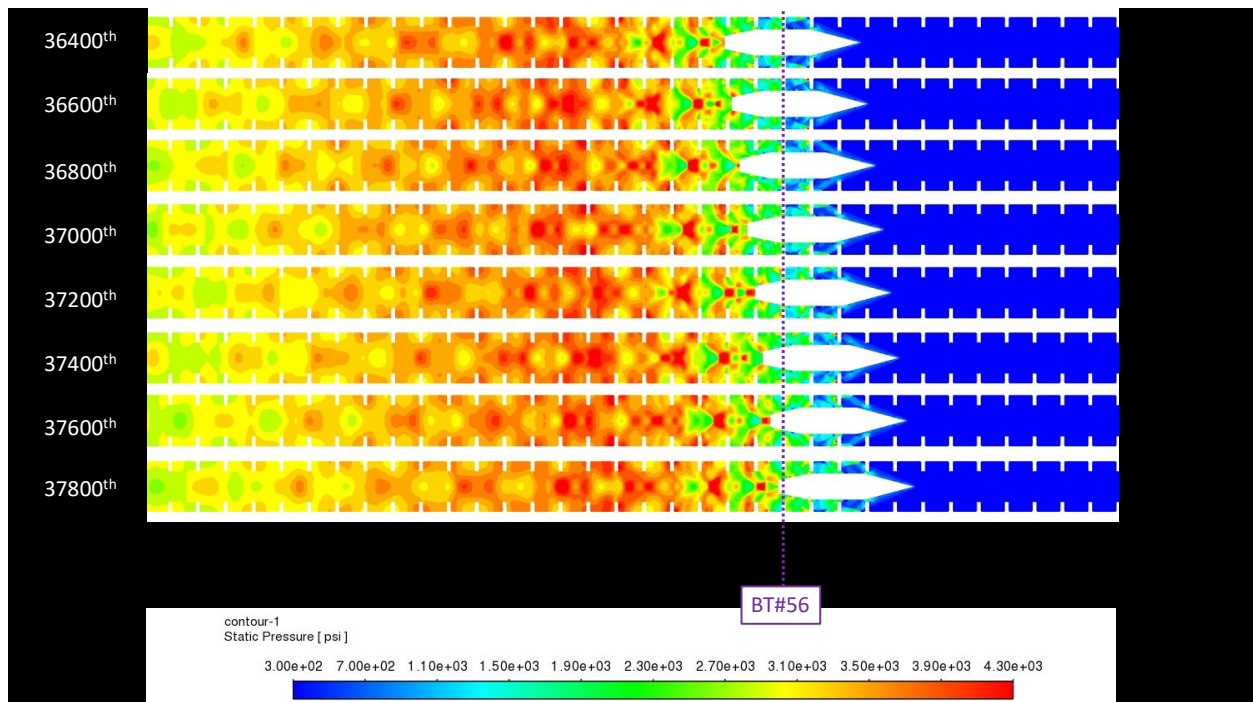


Figure 90 static pressure of P380-2B-12-15 inside BTRA501 at 1.2 km/s near Baffle#56

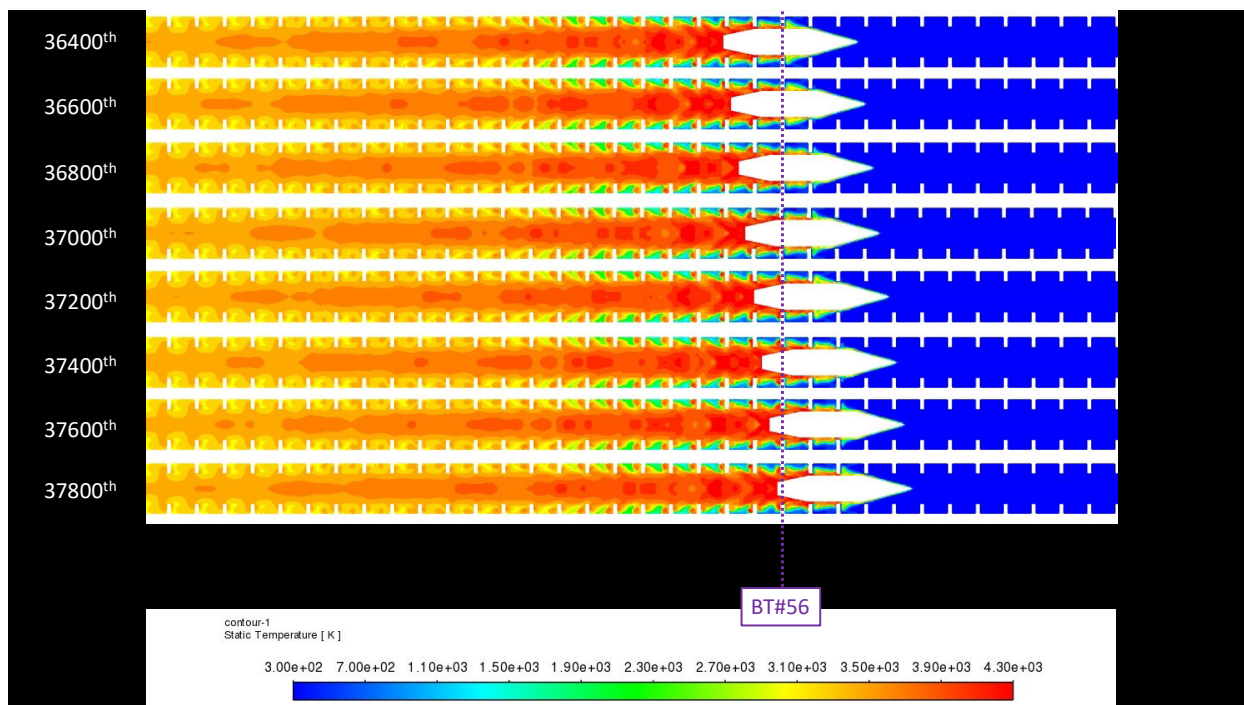


Figure 91 static temperature of P380-2B-12-15 inside BTRA501 at 1.2 km/s near Baffle#56

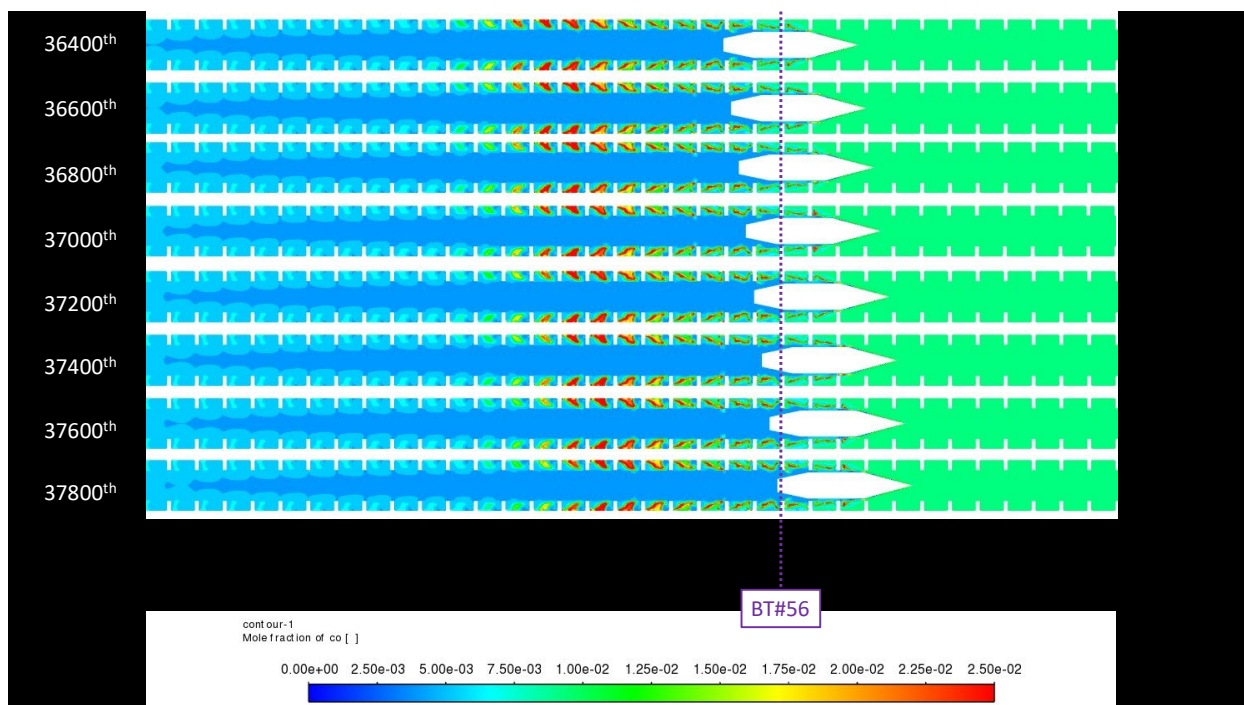


Figure 92 CO-mole fraction of P380-2B-12-15 inside BTRA501 at 1.2 km/s near Baffle#56

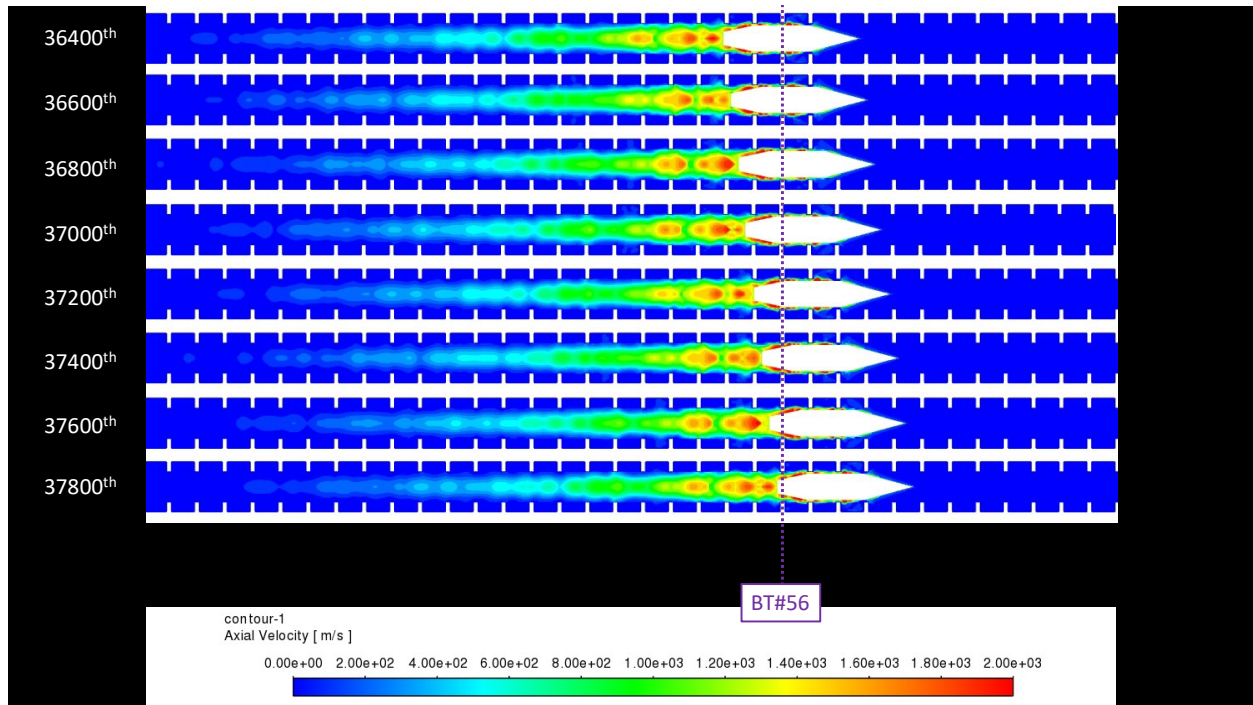


Figure 93 axial velocity of P380-2B-12-15 inside BTRA501 at 1.2 km/s near Baffle#56

3.6.4 P380-2B-12-15 in BTRA501 at 1.4 km/s

The P380-2B-12-15 projectile has a 2.5-unit non-dimensional thrust when it moves at 1.4 km/s inside BTRA501 configuration. The drag contribution from the nose cone is about -3.2-units and relatively constant. While, the base and tail of the projectile continuously generate thrust and roughly reaches a quasi-periodic solution at the last 20-30% of the CFD domain as it is shown in Figure 94. The static pressure, static temperature, CO-mole fraction, and the axial velocity fields are shown during 36400th to 37800th time step in Figure 95, Figure 96, Figure 97, and Figure 98 accordingly.

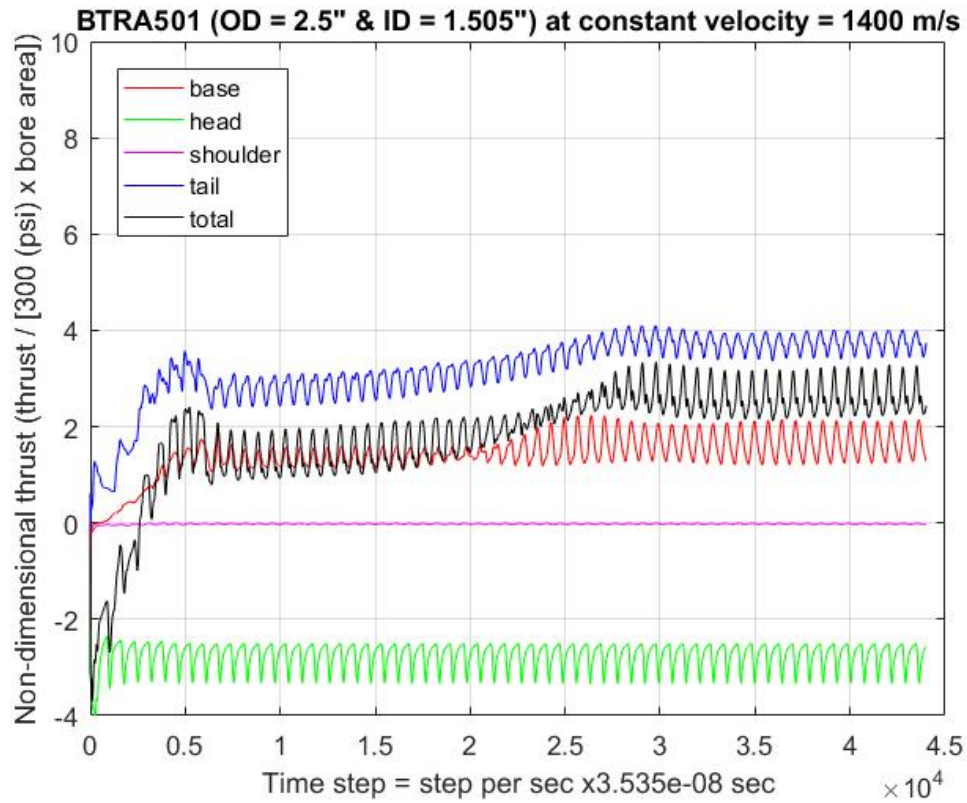


Figure 94 non-dimensional thrust breakdown of P380-2B-12-15 inside BTRA501 at 1.4 km/s

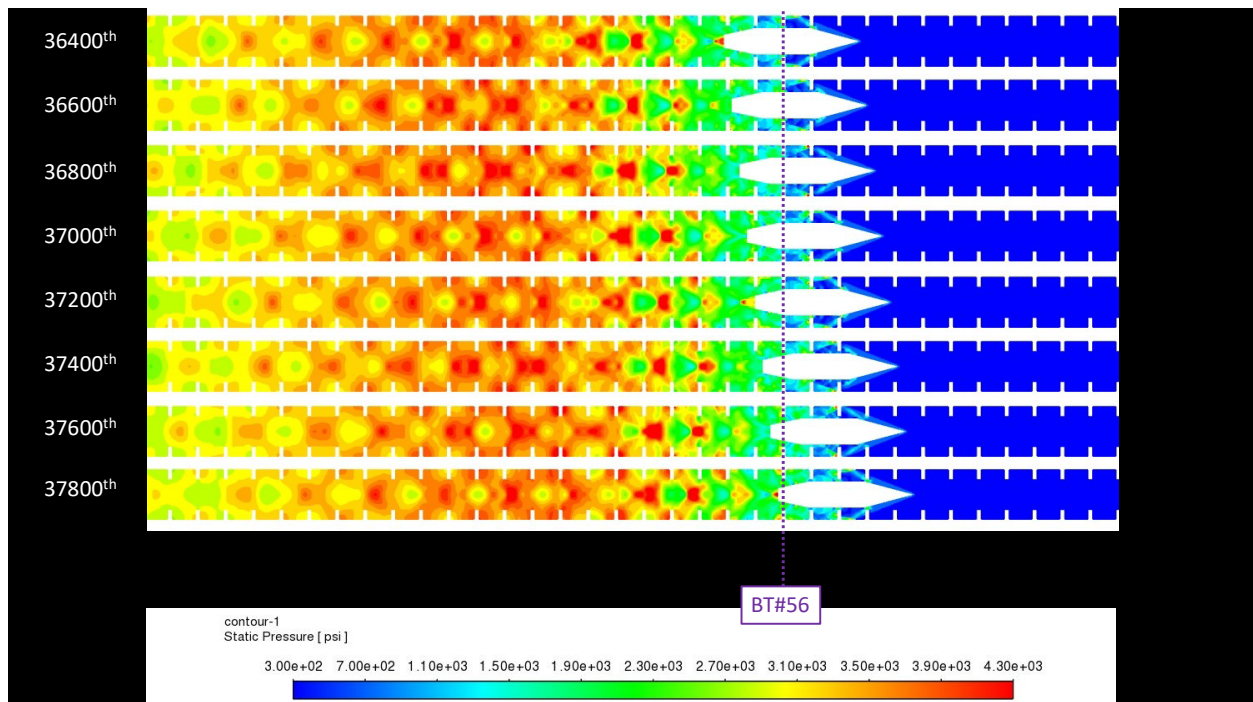


Figure 95 static pressure of P380-2B-12-15 inside BTRA501 at 1.4 km/s near Baffle#56

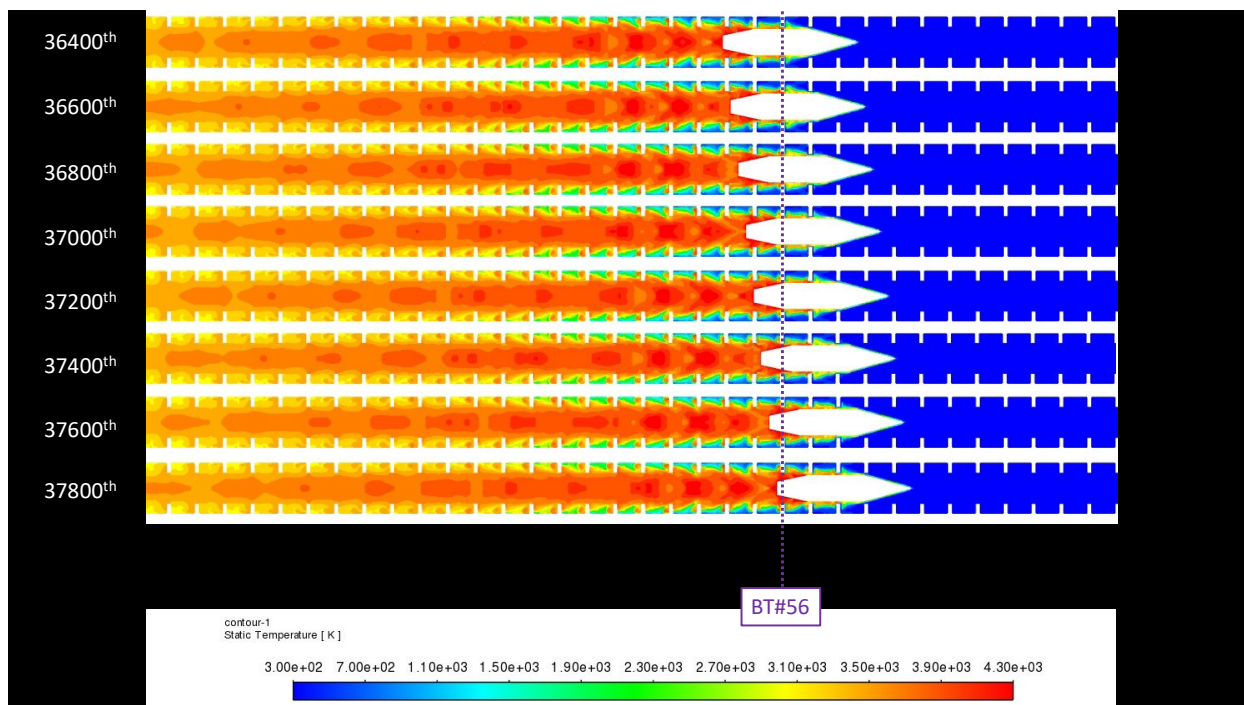


Figure 96 static temperature of P380-2B-12-15 inside BTRA501 at 1.4 km/s near Baffle#56

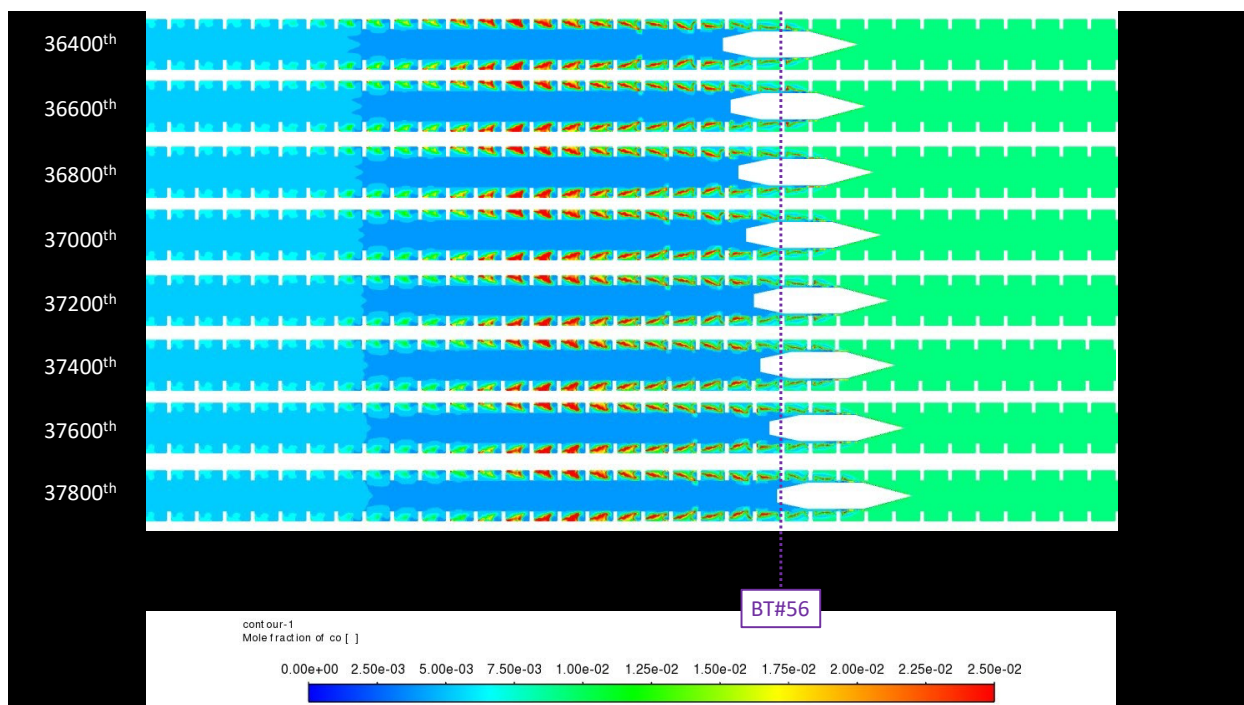


Figure 97 CO-mole fraction of P380-2B-12-15 inside BTRA501 at 1.4 km/s near Baffle#56

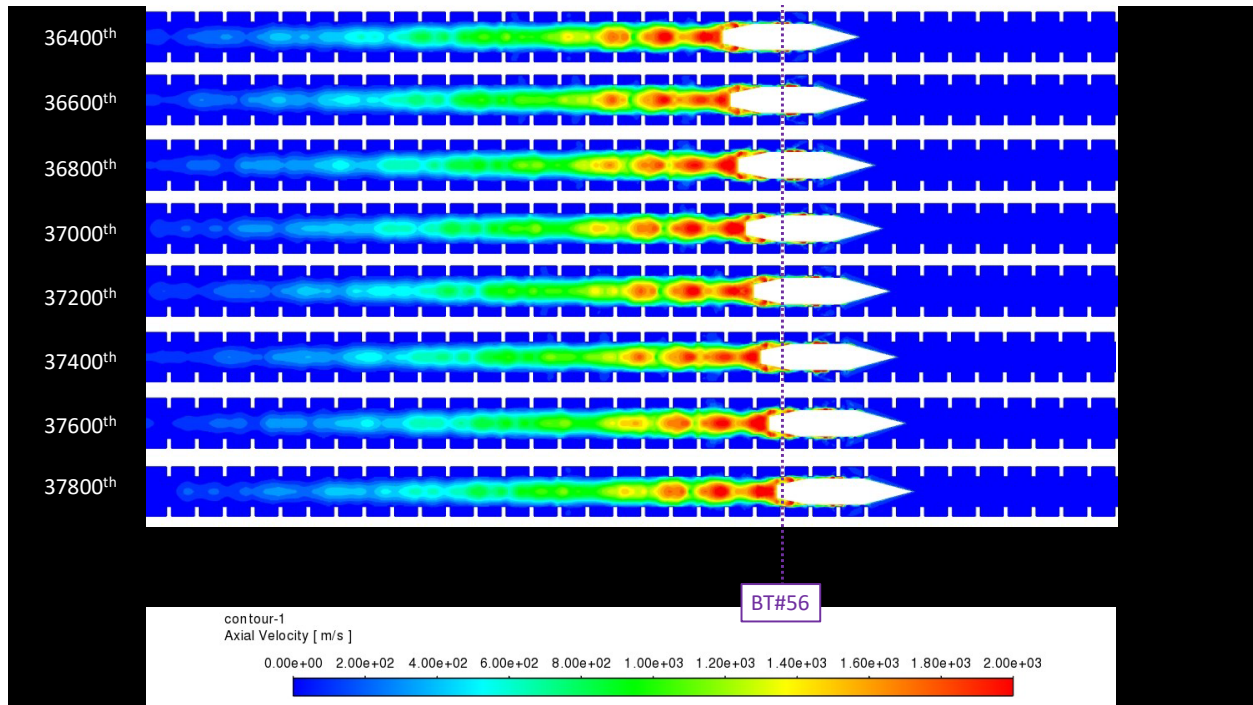


Figure 98 axial velocity of P380-2B-12-15 inside BTRA501 at 1.4 km/s near Baffle#56

3.6.5 P380-3B-12-15 in BTRA501 at 1.0 km/s

The P380-3B-12-15 projectile has a 3.0-non-dimensional thrust when it moves at 1.0 km/s inside BTRA501 configuration. However, the long projectile unstarts at 1.0 km/s. The drag contribution from the nose cone starts around -2.0-unit, but it increases as a function of time and reaches about -3.6-unit toward the latter part of the simulation. While, the base and tail of the projectile initially generate thrust with a positive rate and then with a negative rate when the nose cone shows an unstaring behavior. Untimely, the non-dimensional thrust reaches a quasi-periodic solution at the last 10-15% of the CFD domain as it is shown in Figure 99. The static pressure, static temperature, CO-mole fraction, and the axial velocity fields are shown during 36100th to 37500th time step in Figure 100, Figure 101, Figure 102, and Figure 103 accordingly.

BTRA501 (OD = 2.5" & ID = 1.505") at velocity = 1000 m/s with Long Projectile

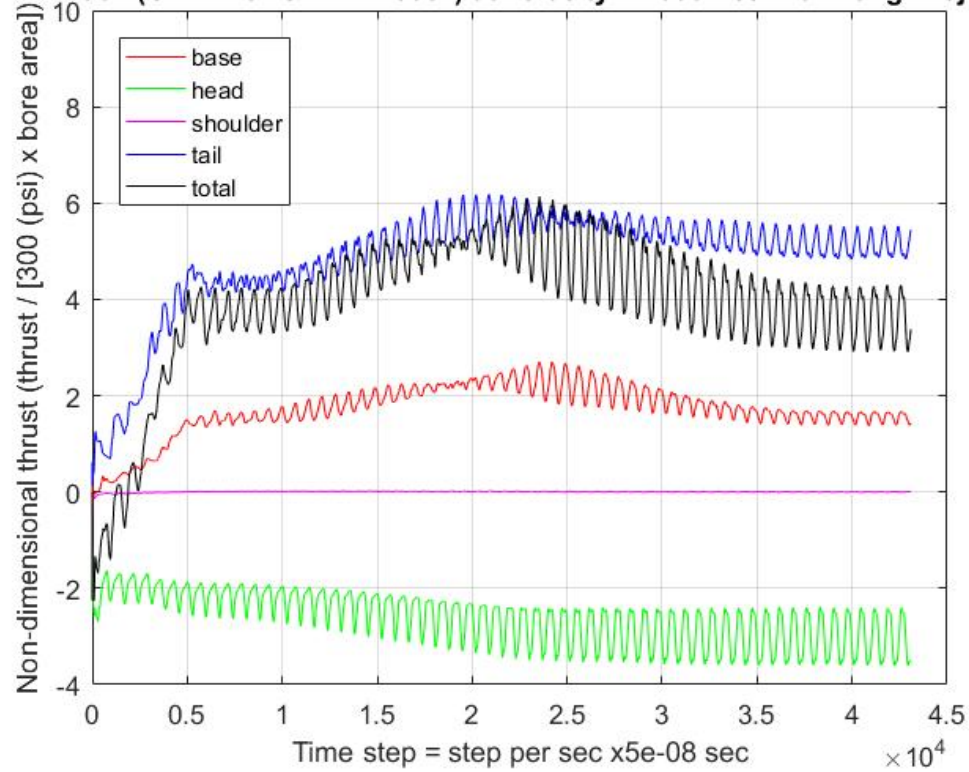


Figure 99 non-dimensional thrust breakdown of P380-3B-12-15 inside BTRA501 at 1.0 km/s

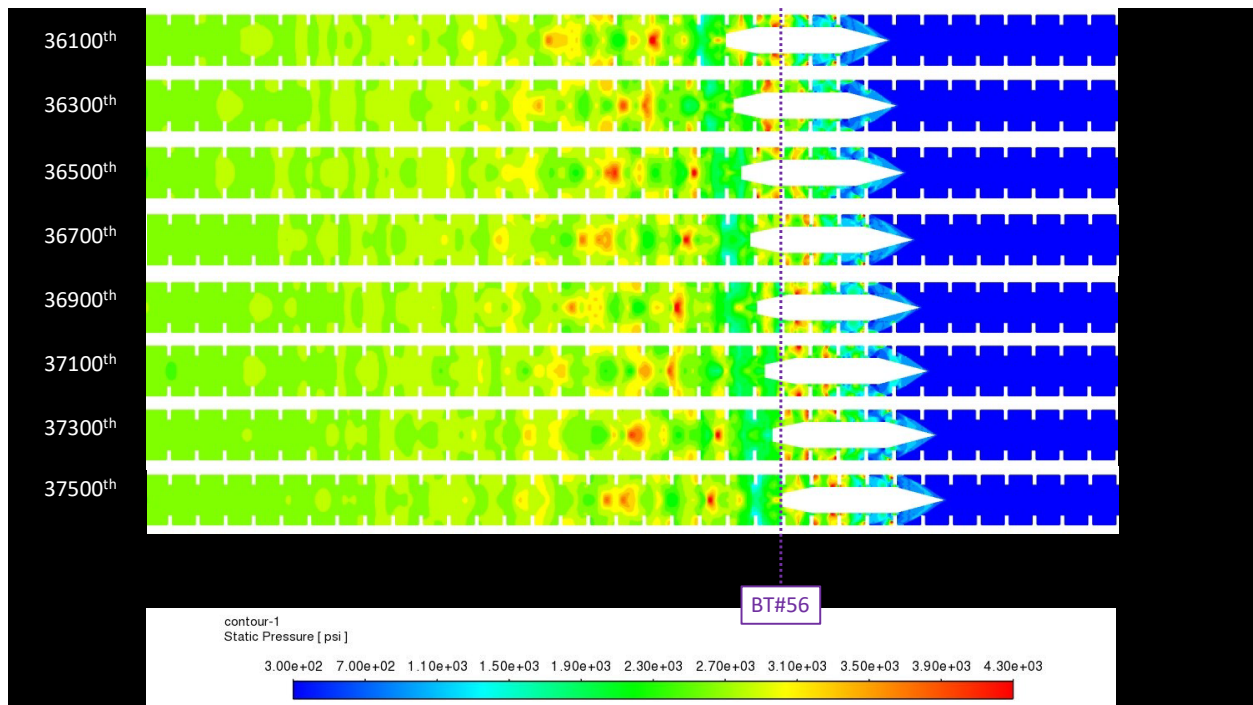


Figure 100 static pressure of P380-3B-12-15 inside BTRA501 at 1.0 km/s near Baffle#56

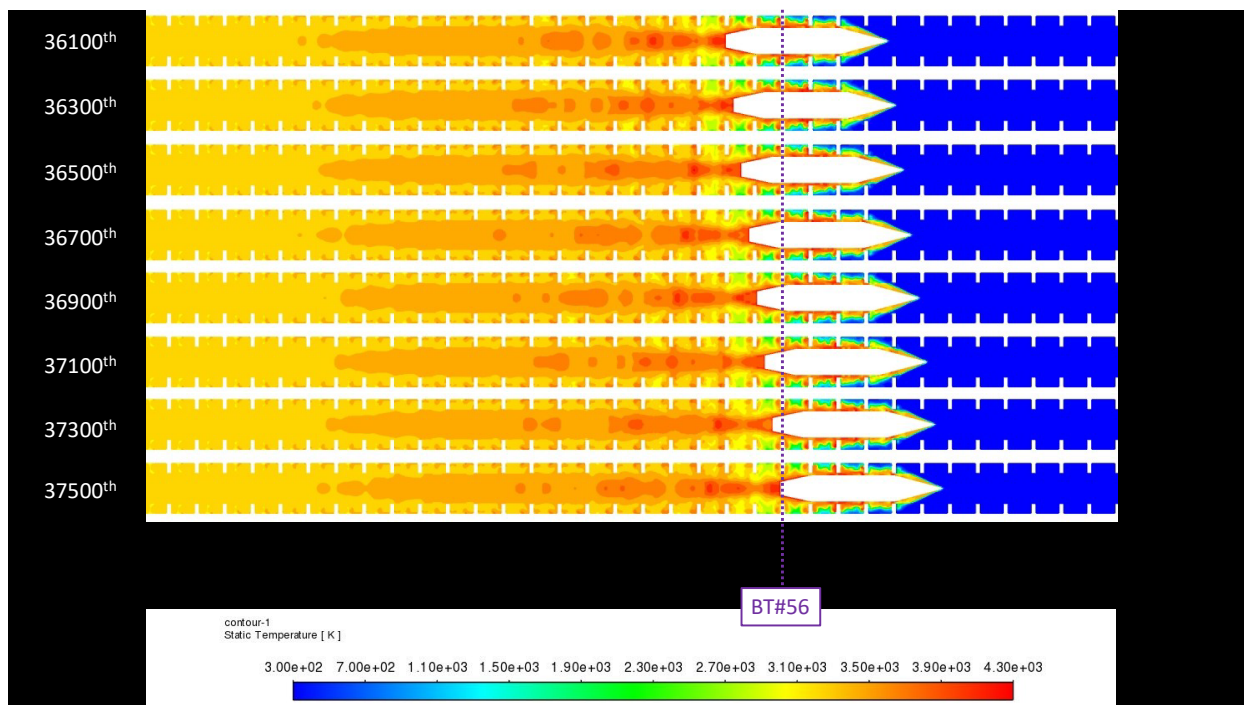


Figure 101 static temperature of P380-3B-12-15 inside BTRA501 at 1.0 km/s near Baffle#56

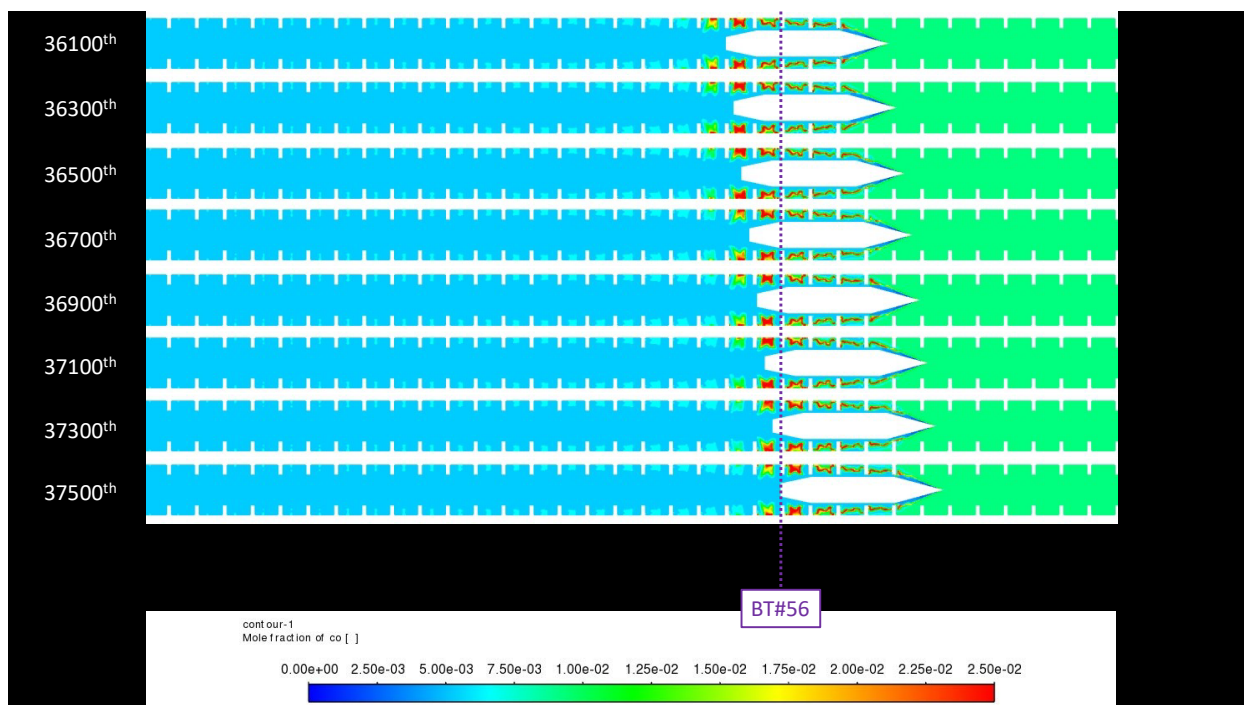


Figure 102 CO-mole fraction of P380-3B-12-15 inside BTRA501 at 1.0 km/s near Baffle#56

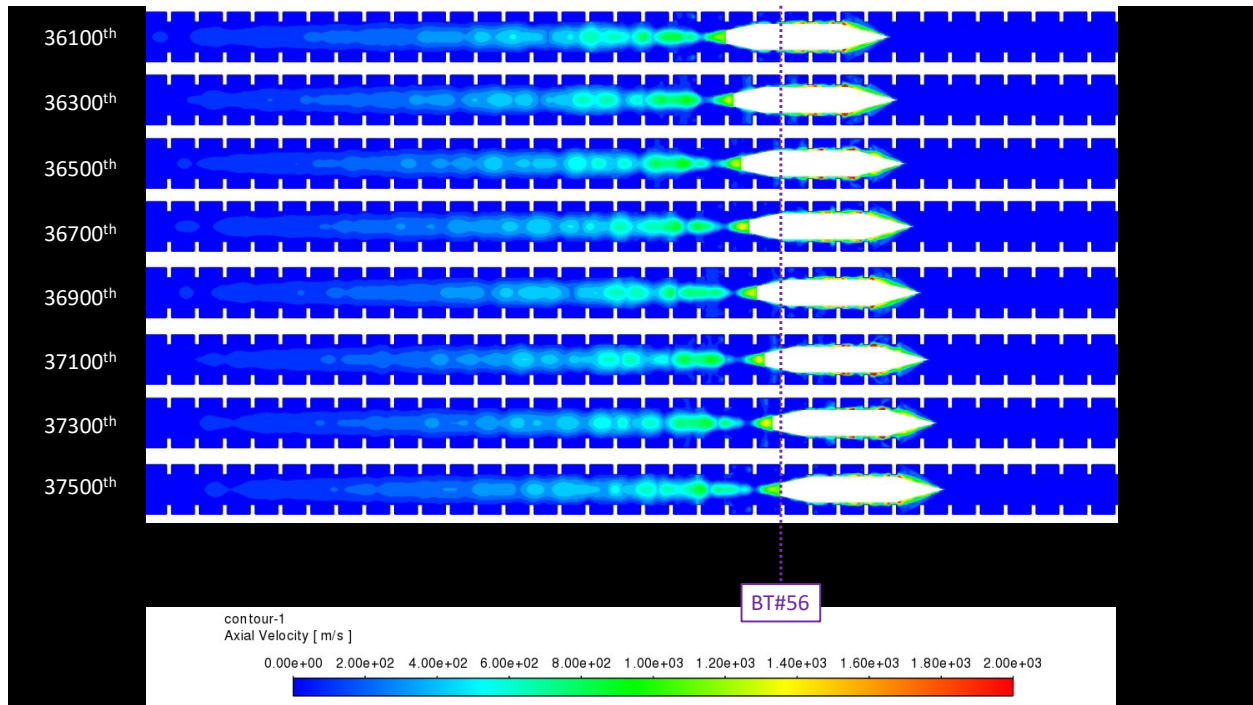


Figure 103 axial velocity of P380-3B-12-15 inside BTRA501 at 1.0 km/s near Baffle#56

3.6.6 P380-3B-12-15 in BTRA501 at 1.2 km/s

The P380-3B-12-15 projectile has a 5.0-non-dimensional thrust when it moves at 1.2 km/s inside BTRA501 configuration. Unlike 1.0 km/s case, the long projectile remains started at 1.2 km/s. The drag contribution from the nose cone starts around -3.0-unit and remains relatively constant. While, the base and tail of the projectile continuously generate thrust and roughly reaches a quasi-periodic solution at the last 10-15% of the CFD domain as it is shown in Figure 104. The static pressure, static temperature, CO-mole fraction, and the axial velocity fields are shown during 36400th to 37800th time step in Figure 105, Figure 106, Figure 107, and Figure 108 accordingly.

BTRA501 (OD = 2.5" & ID = 1.505") at velocity = 1200 m/s with Long Projectile

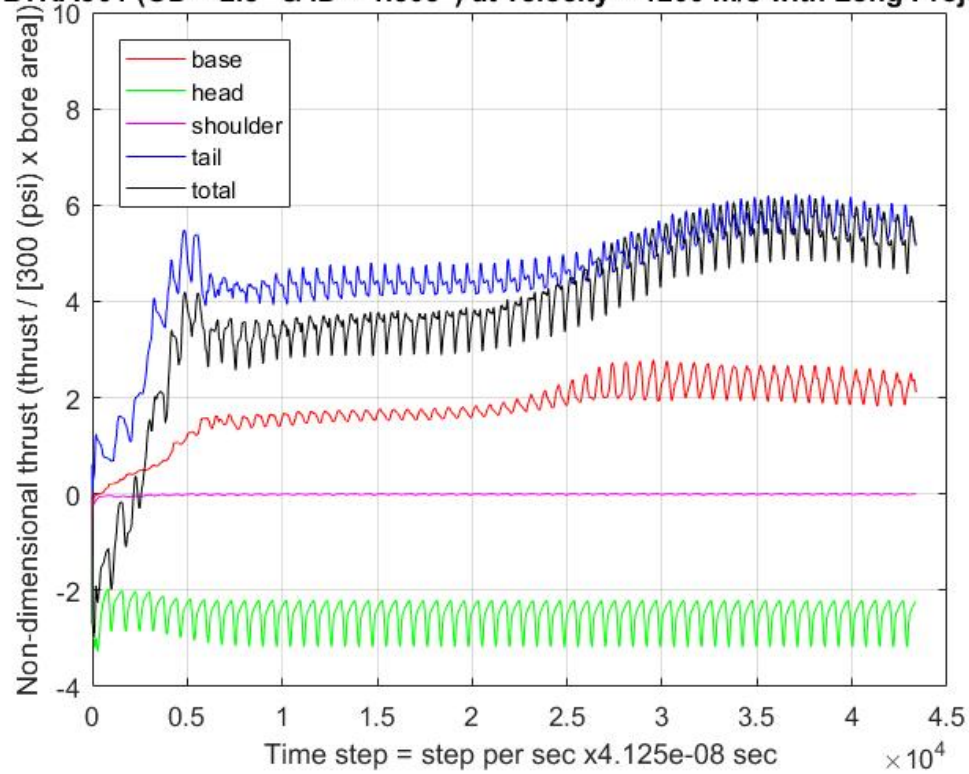


Figure 104 non-dimensional thrust breakdown of P380-3B-12-15 inside BTRA501 at 1.2 km/s

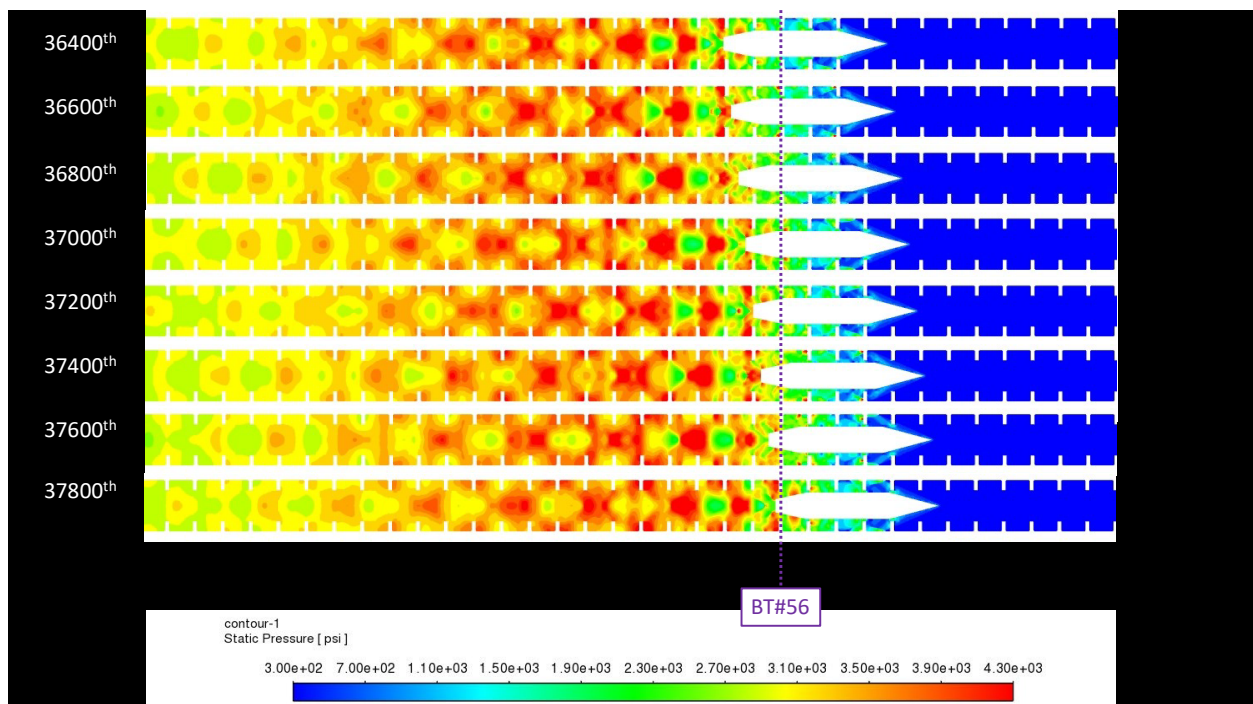


Figure 105 static pressure of P380-3B-12-15 inside BTRA501 at 1.2 km/s near Baffle#56

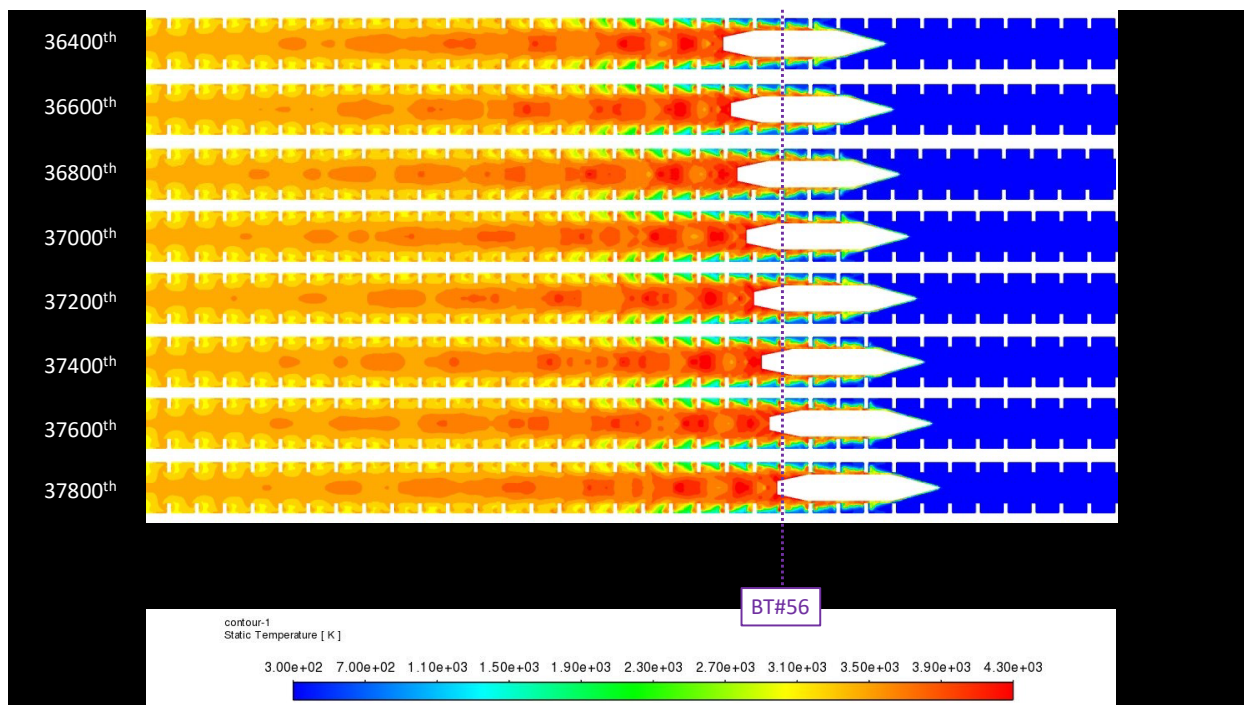


Figure 106 static temperature of P380-3B-12-15 inside BTRA501 at 1.2 km/s near Baffle#56

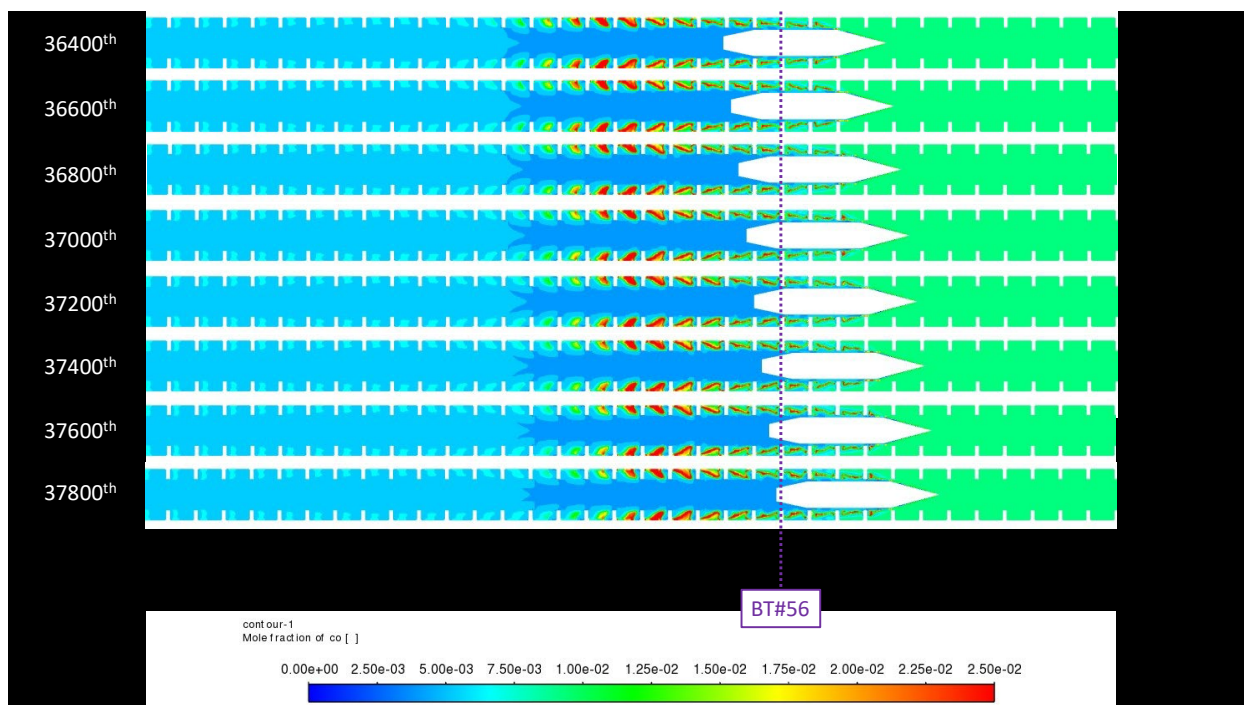


Figure 107 CO-mole fraction of P380-3B-12-15 inside BTRA501 at 1.2 km/s near Baffle#56

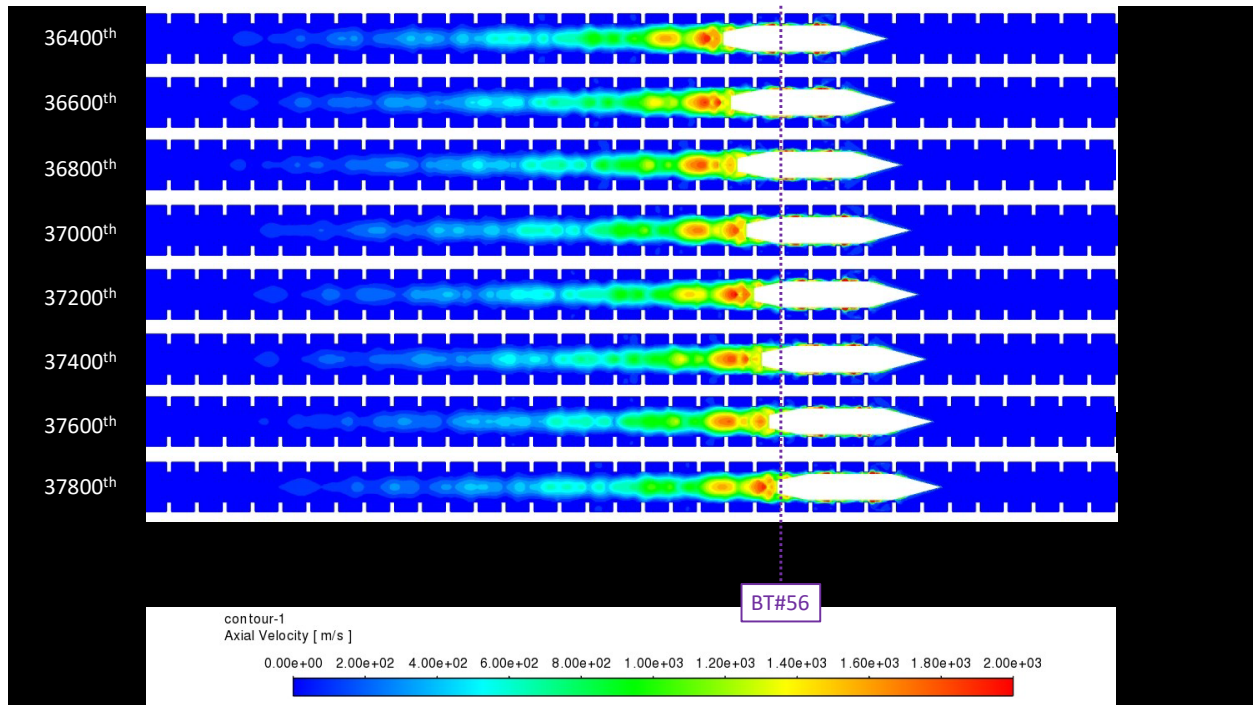


Figure 108 axial velocity of P380-3B-12-15 inside BTRA501 at 1.2 km/s near Baffle#56

3.6.7 P380-2B-12-15 (1.0 vs. 1.1 vs. 1.2 vs. 1.4 km/s) vs. P380-3B-12-15 (1.0 vs. 1.2 km/s) in BTRA501 Discussion

The non-dimensional thrust of P380-2B-12-15 moving at 1.0, 1.1, 1.2, and 1.4 km/s in BTRA501 comparison is shown in Figure 109. As the projectile velocity increases, the non-dimensional thrust decreases accordingly. Also, the continuous increase in non-dimensional thrust during simulation at each constant velocity cases indicates that the flow behind the projectile wants to accelerate to a higher velocity and exerts higher forces on the projectile. However, since the simulation is conducted at a constant velocity for these cases, the projectile is unable to reach a higher velocity while the flow is accelerating to a higher velocity. These results suggest to investigate the performance of BTRA at a constant acceleration which is discussed in the latter subsection. The high-pressure region behind the base remains very close to the base at

lower velocity. While at higher velocity, the high-pressure region moves downstream relative to the base reducing the non-dimensional thrust. The static pressure, CO-mole fraction, and axial velocity field comparisons are shown in Figure 110, Figure 111, and Figure 112 for completeness.

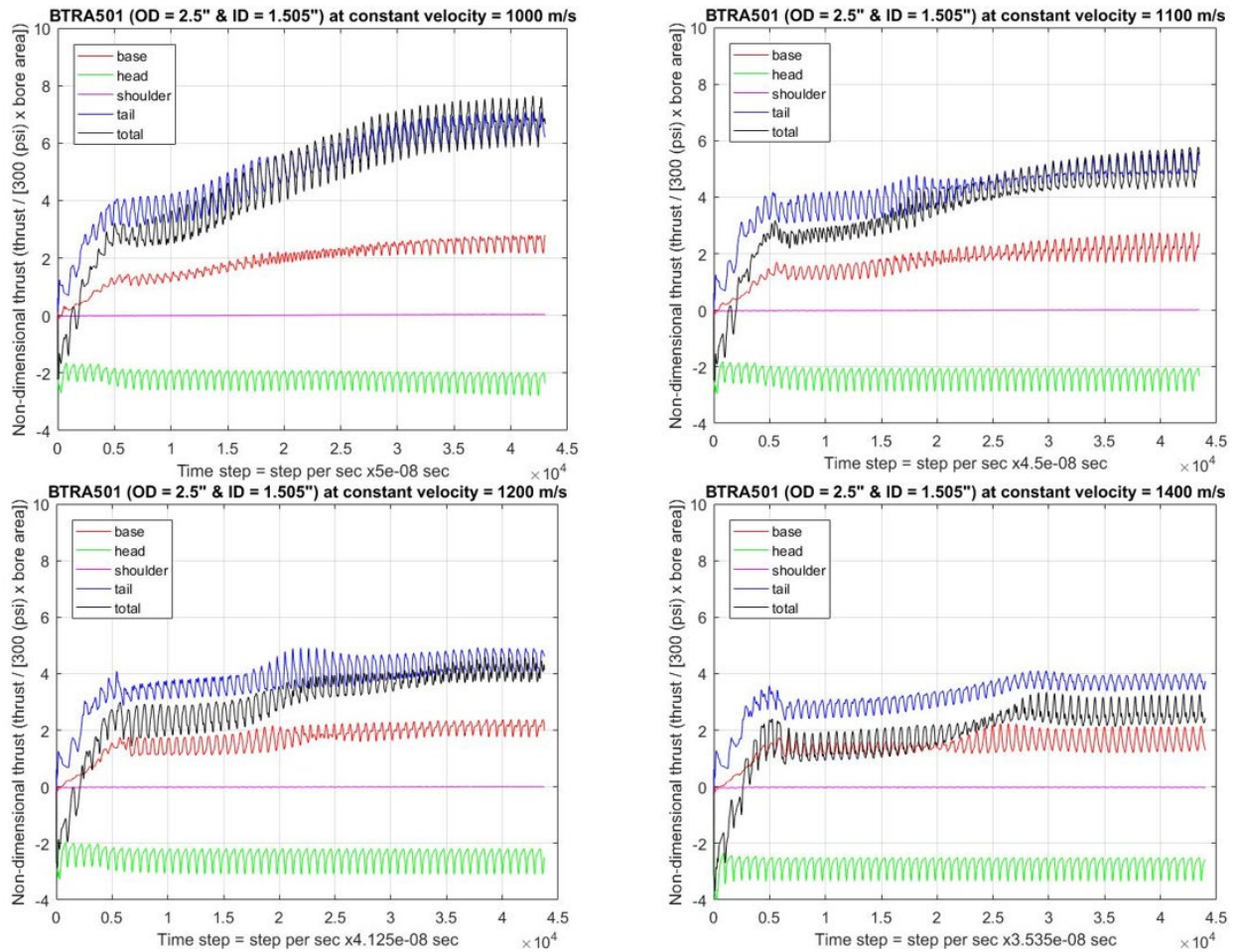


Figure 109 non-dimensional thrust of P380-2B-12-15 in BTRA501 at 1.0 vs. 1.1 vs. 1.2 vs. 1.4 km/s comparison

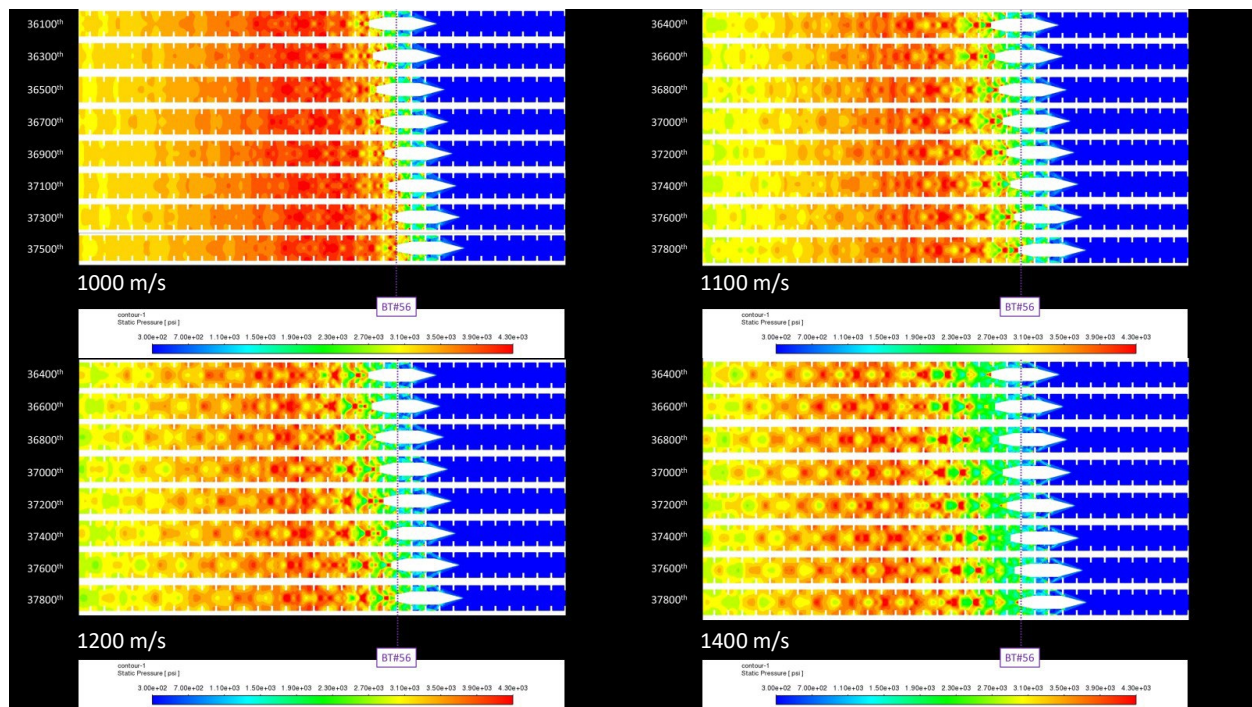


Figure 110 static pressure field comparison of P380-2B-12-15 in BTRA501 at 1.0 vs. 1.1 vs. 1.2 vs. 1.4 km/s comparison

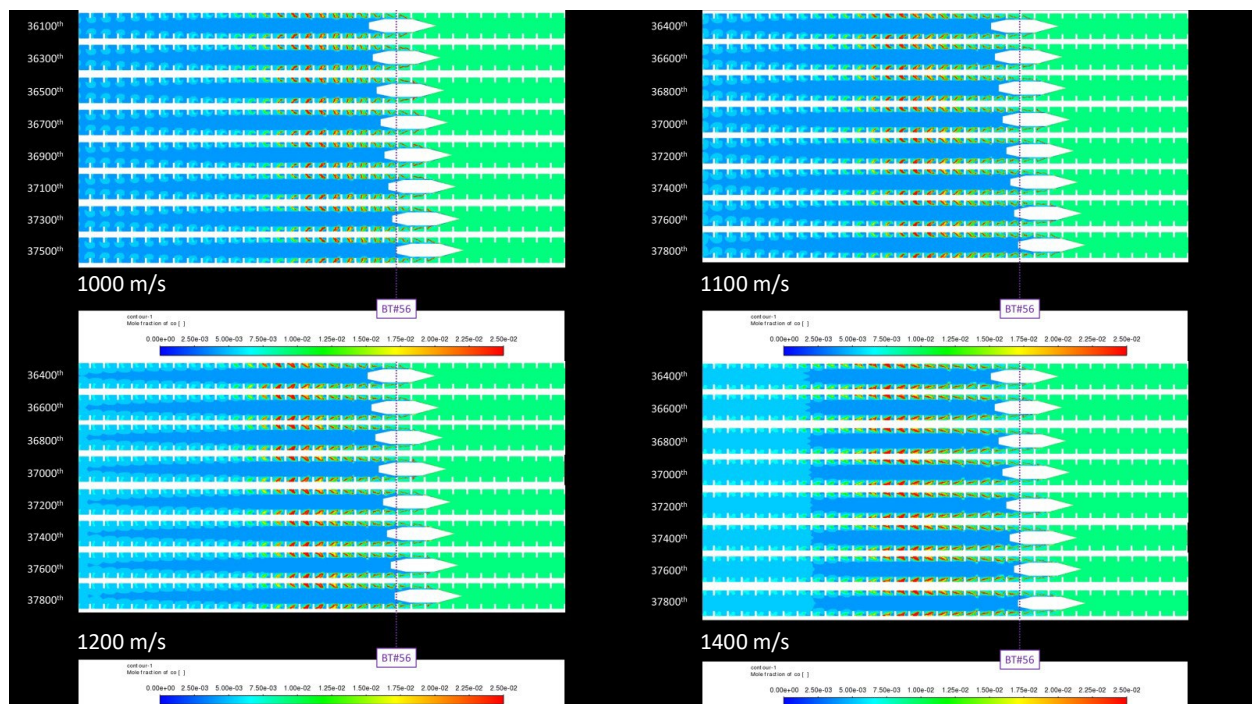


Figure 111 CO-mole fraction field comparison of P380-2B-12-15 in BTRA501 at 1.0 vs. 1.1 vs. 1.2 vs. 1.4 km/s comparison

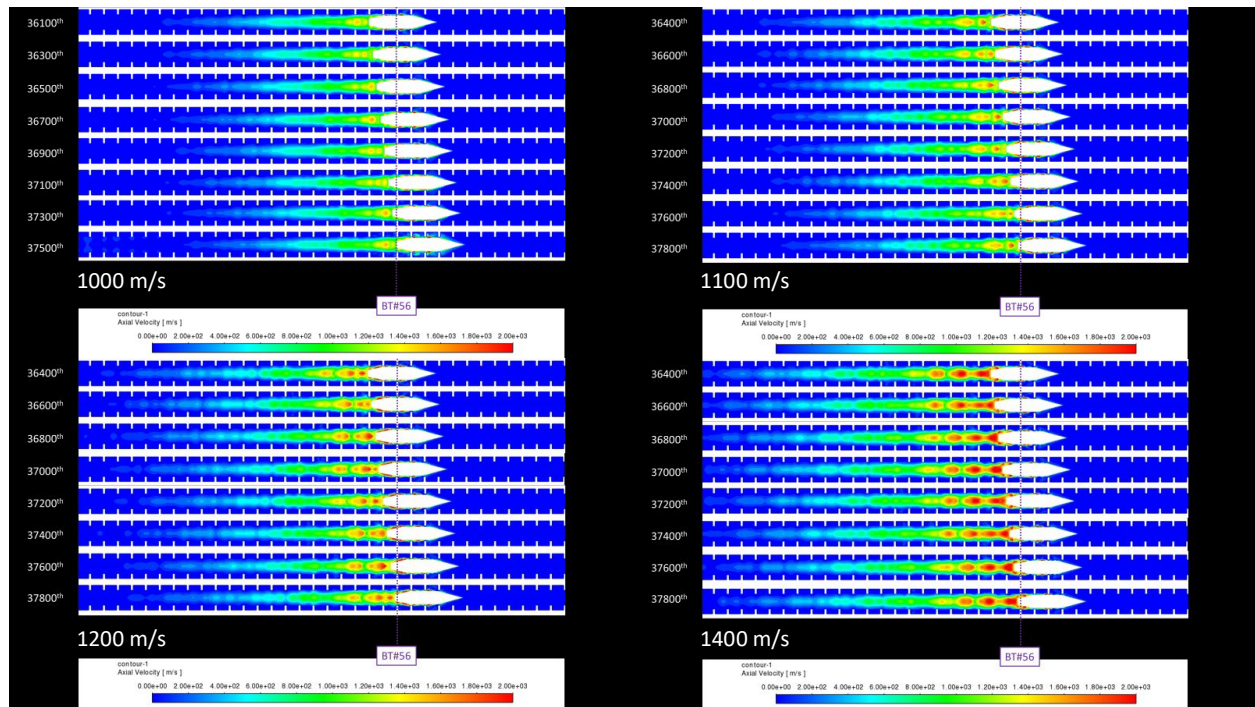


Figure 112 axial velocity field comparison of P380-2B-12-15 in BTRA501 at 1.0 vs. 1.1 vs. 1.2 vs. 1.4 km/s comparison

The non-dimensional thrust of P380-2B-12-15 and P380-3B-12-15 moving at 1.0 and 1.2 km/s in BTRA501 comparison is shown in Figure 113. As the short projectile velocity increases, the non-dimensional thrust decreases accordingly. However, the long projectile unstarts at 1.0 km/s, but it remains started at 1.2 km/s. As mentioned before, the continuous increase in non-dimensional thrust indicates that the flow behind the projectile wants to accelerate to a higher velocity and exert higher forces on the projectile. This observation remains true for the long projectile at 1.0 km/s. However, the acceleration of high energetic region surge passes the shoulder and ultimately reaches the nose cone and unstarts the projectile known as sonic diffuser unstart [26]. It is speculated if the computational domain was longer, the projectile non-dimensional thrust continuously decrease to a lower value. Note that the static pressure contours shown in Figure

114 have the same dynamic range. Examining the pressure field indicate that some higher-pressure pockets are present and visible on the long projectile when it moves at 1.0 km/s, whereas those high-pressure regions do not exist on the other 3 cases. The high-pressure region behind the base remains very close to the base at lower velocity. While at higher velocity, the high-pressure region moves downstream relative the base reducing the non-dimensional thrust. The static pressure, CO-mole fraction, and axial velocity field comparisons are shown in Figure 114, Figure 115, and Figure 116 for completeness.

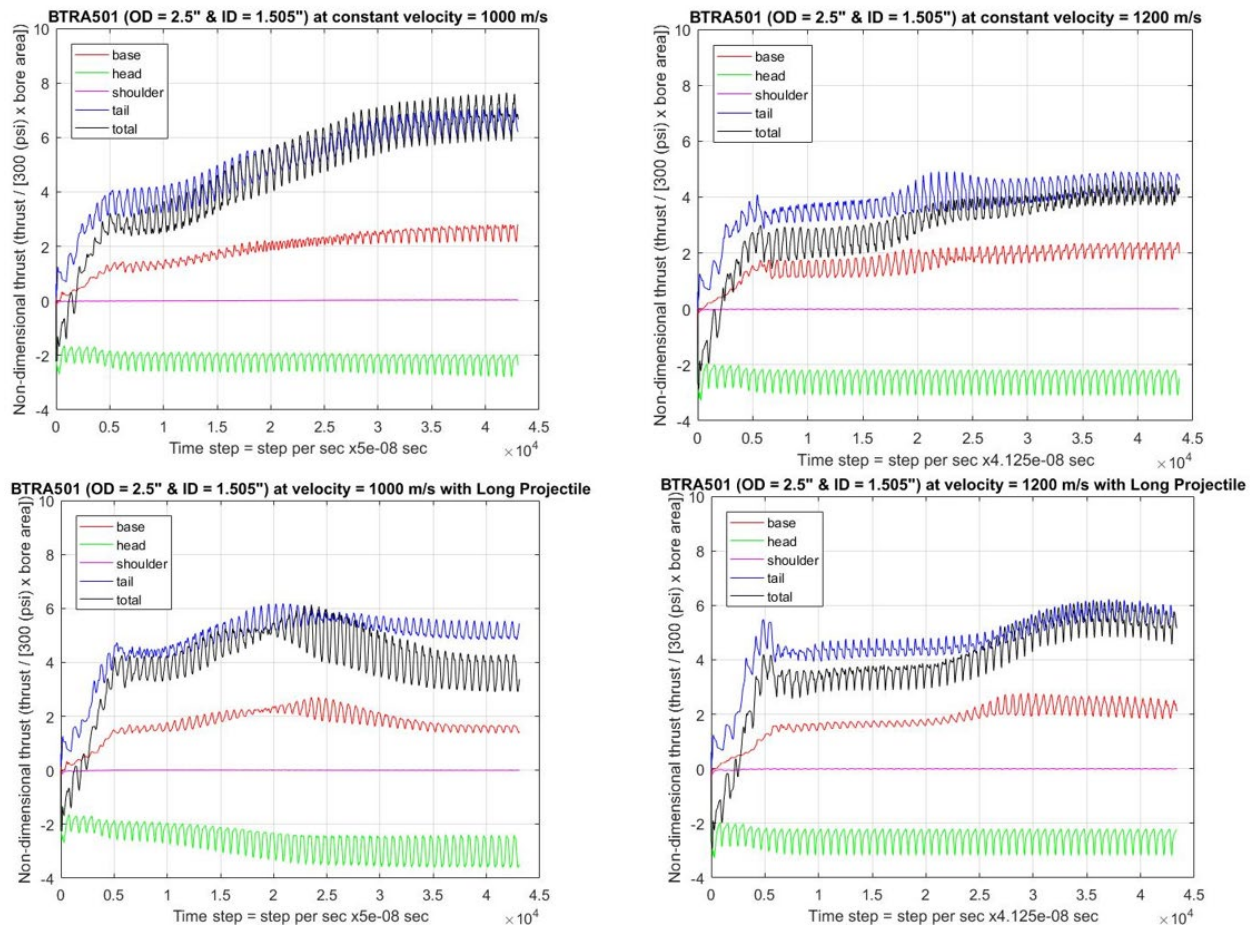


Figure 113 non-dimensional thrust of P380-2B-12-15 and P380-3B-12-15 in BTRA501 at 1.0 vs. 1.2 km/s comparison

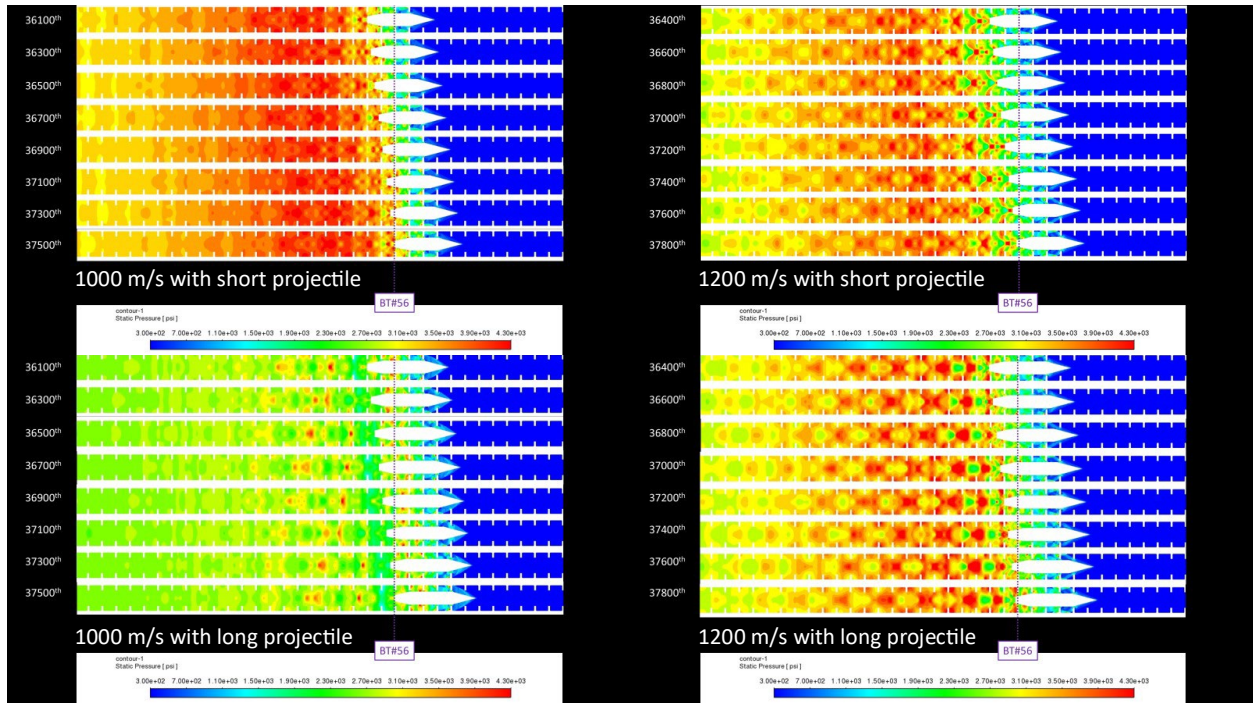


Figure 114 static pressure field comparison of P380-2B-12-15 and P380-3B-12-15 in BTRA501 at 1.0 vs. 1.2 km/s comparison

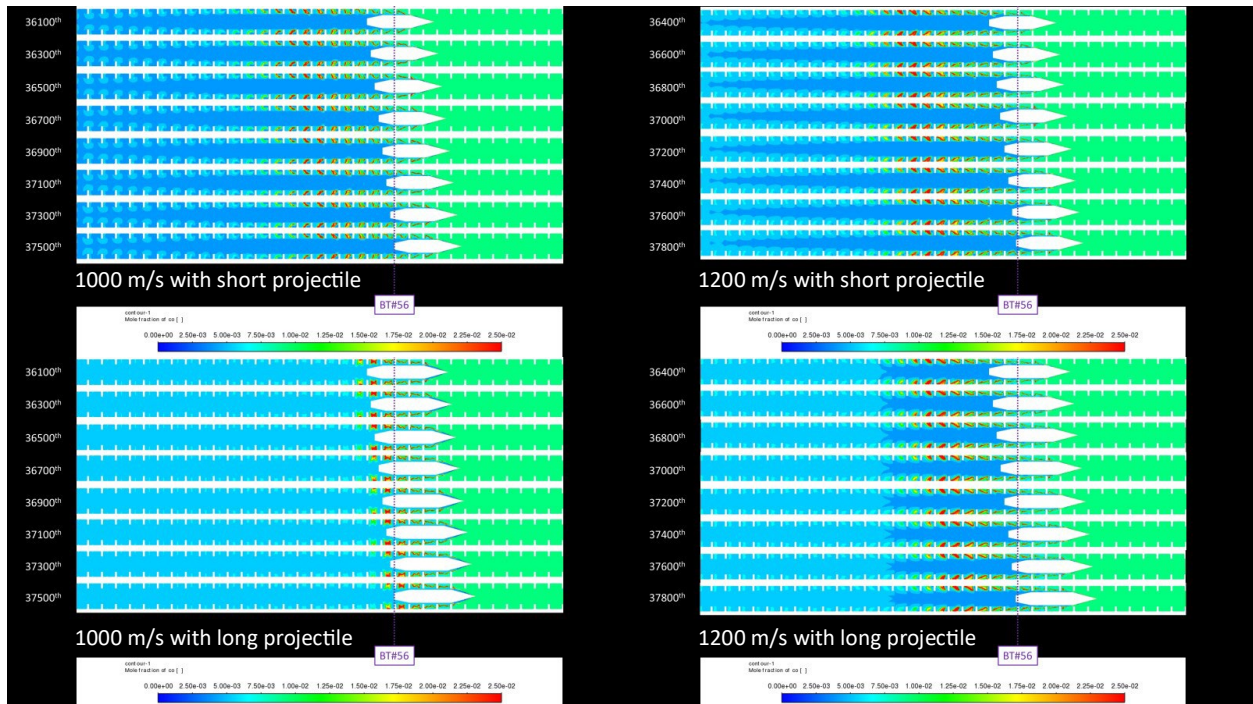


Figure 115 CO-mole fraction field comparison of P380-2B-12-15 and P380-3B-12-15 in BTRA501 at 1.0 vs. 1.2 km/s comparison

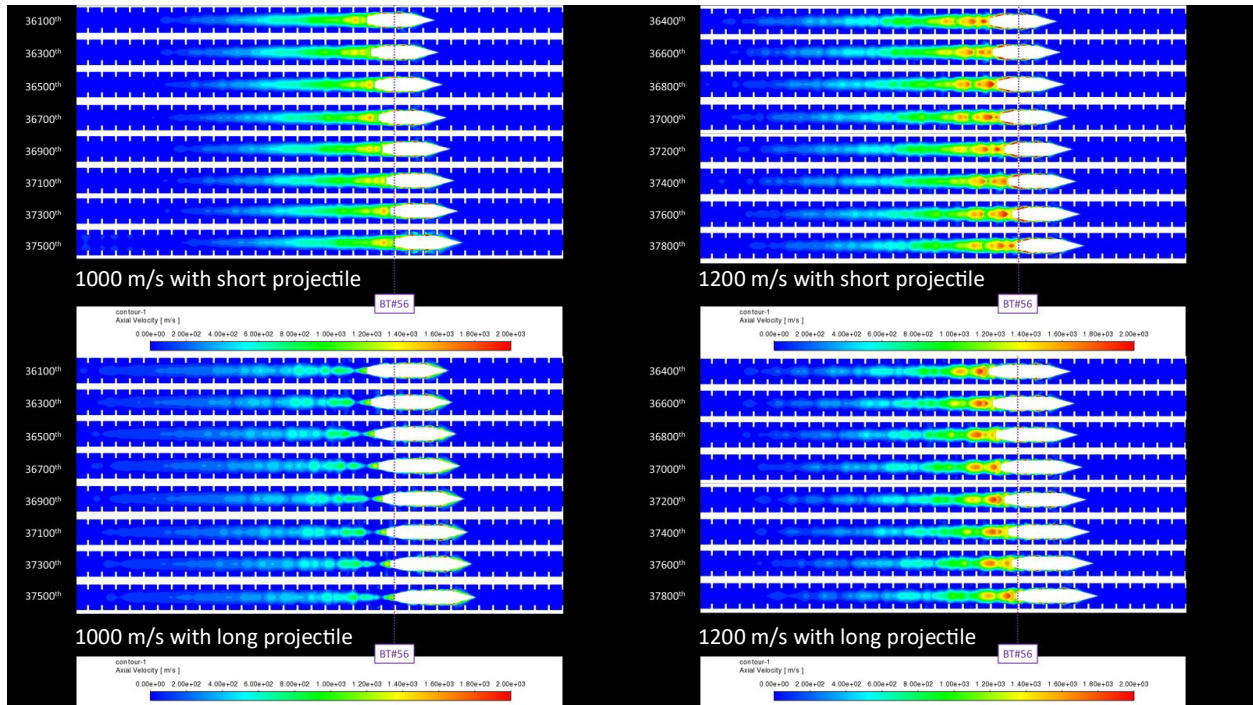


Figure 116 axial velocity field comparison of P380-2B-12-15 and P380-3B-12-15 in BTRA501 at 1.0 vs. 1.2 km/s comparison

3.7 Impact of Constant Acceleration on Non-Dimensional Thrust

The purpose of these simulations is to identify the impact of constant acceleration on the projectile thrust performance in BTRA501 configuration. The effect of constant acceleration is investigated for a few cases near the velocity range of interest, i.e., 1.0, 1.1 and 1.2 km/s using CFD simulation. One case is that P380-2B-12-15 (short projectile) accelerates at $8000g \text{ m/s}^2$ from 1.0 to 1.1 km/s after a few thousand iterations after moving a constant velocity of 1.0 km/s. Then, Fluent UDF [52] is modified (with a logical if-condition) to increase the velocity at a constant rate at 18750^{th} time step to accelerate the projectile by $8000g$ to reach 1.1 km/s near 43000^{th} time step toward the end of the computational domain. In a similar simulation, the short projectiles accelerate at $19656g \text{ m/s}^2$ from 1.0 to 1.2 km/s after a few thousand iterations after moving a

constant velocity of 1.0 km/s. Then, UDF accelerates the projectile at 18750th time step to reach 1.2 km/s near 44300th time step accordingly. The last case is to accelerate P380-3B-12-15 (long projectile) by 19656g m/s² from 1.0 to 1.2 km/s and compare its performance against the short projectile. All these accelerated cases are simulated at 20.4 atm fill pressure and 300 K fill temperature inside 1CH₄+2O₂+4.67N₂ mixture. The test conditions are listed in Table 12. This table is identical to Table 8 in Section 3.3 (3.3 Geometries Used in CFD Modeling of BTRA, Objectives, and Test Matrices) and it is repeated here for completeness. As mentioned before, the increase of non-dimensional thrust of a projectile moving a constant velocity suggests that flow is accelerating behind the projectile and physically should exert extra force on the projectile and pushes it toward a higher velocity. The comparison of the non-dimensional thrust of the projectile at constant velocities against the relevant constant acceleration case is shown in this section.

Table 12 test matrix: constant acceleration impact on baseline and alternative projectile in BTRA501 configuration

8000g m/s² (1.0 to 1.1 km/s)		19656g m/s²(1.0 to 1.2 km/s)
Baseline Proj.	Started	Started
Alternative Proj.	-----	Started

A short content associated with the non-dimensional thrust and relevant flow field maps for these 3 cases are shown in the subsequent sections. Then, their performances are compared at the end of this section. Similar to Sections 3.5-3.6, Baffle#56 was chosen as the reference baffle to extract the flow field around this location in the laboratory frame of reference. The rationale

behind choosing Baffle#56 was to pick a baffle location near end of the CFD domain where the flow may have reached the quasi-periodic solution.

3.7.1 P380-2B-12-15 with 8000g Constant Acceleration (1.0 to 1.1 km/s)

The P380-2B-12-15 (short projectile) initially has a 4.2-unit non-dimensional thrust when it moves at a constant velocity of 1.0 km/s inside BTRA501 configuration until 18750th time step. Then, projectile starts to accelerate with 8000g and it reaches a maximum 5.8-unit non-dimensional thrust around 32000th time step when the projectile velocity is around 1050 m/s. Then, the non-dimensional thrust decreases to around 5.0-unit around 45000th time step. The drag contribution from the nose cone starts around -2.5-unit and remains relatively constant even when the projectile accelerates. The thrust contribution from the base and tail of the projectile follow the total thrust trend. The base shows more thrust fluctuation toward the end of the simulation (higher velocity near 1.1 km/s), while the tail shows less thrust fluctuation for the same time duration. Overall, the 8000g accelerated cases does not reach a quasi-periodic solution. However, the non-dimensional thrust toward the end of the simulation, i.e., near 1.1 km/s, is very similar to that of the constant velocity of 1.1 km/s case. The thrust performance of the short projectile with 8000g acceleration is shown in Figure 117. The static pressure, static temperature, CO-mole fraction, and the axial velocity fields are shown during 41200th to 42600th time step in Figure 118, Figure 119, Figure 120, and Figure 121 accordingly. Note that the velocity of the projectile is about 1086 m/s at 41200th time step and about 1092 m/s at 42600th time step accordingly.

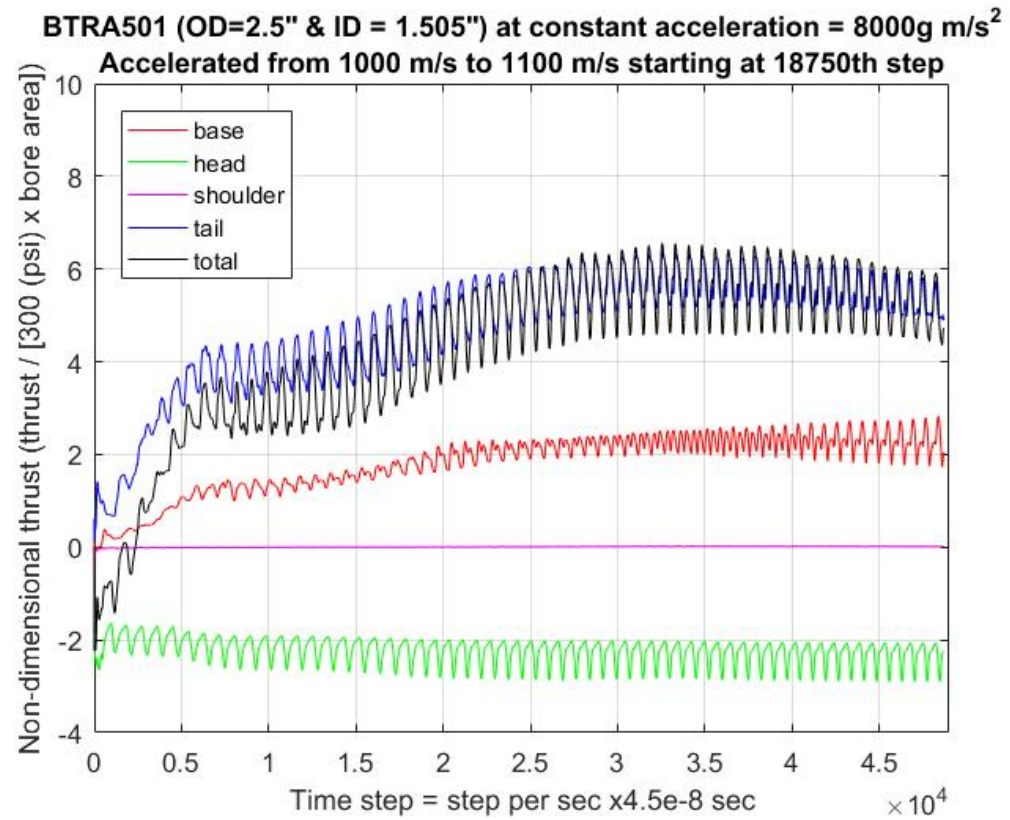


Figure 117 non-dimensional thrust breakdown of P380-2B-12-15 inside BTRA501 at 8000g constant acceleration (1.0 to 1.1 km/s)

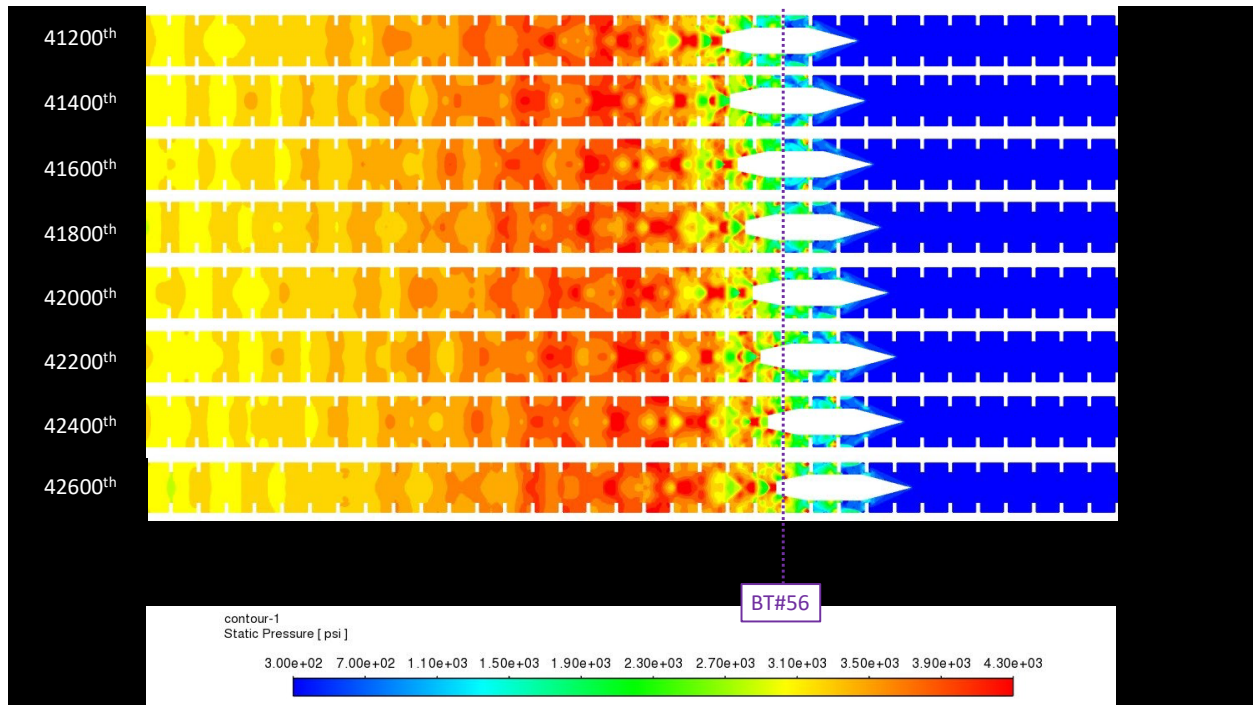


Figure 118 static pressure of P380-2B-12-15 inside BTRA501 at 8000g constant acceleration near Baffle#56

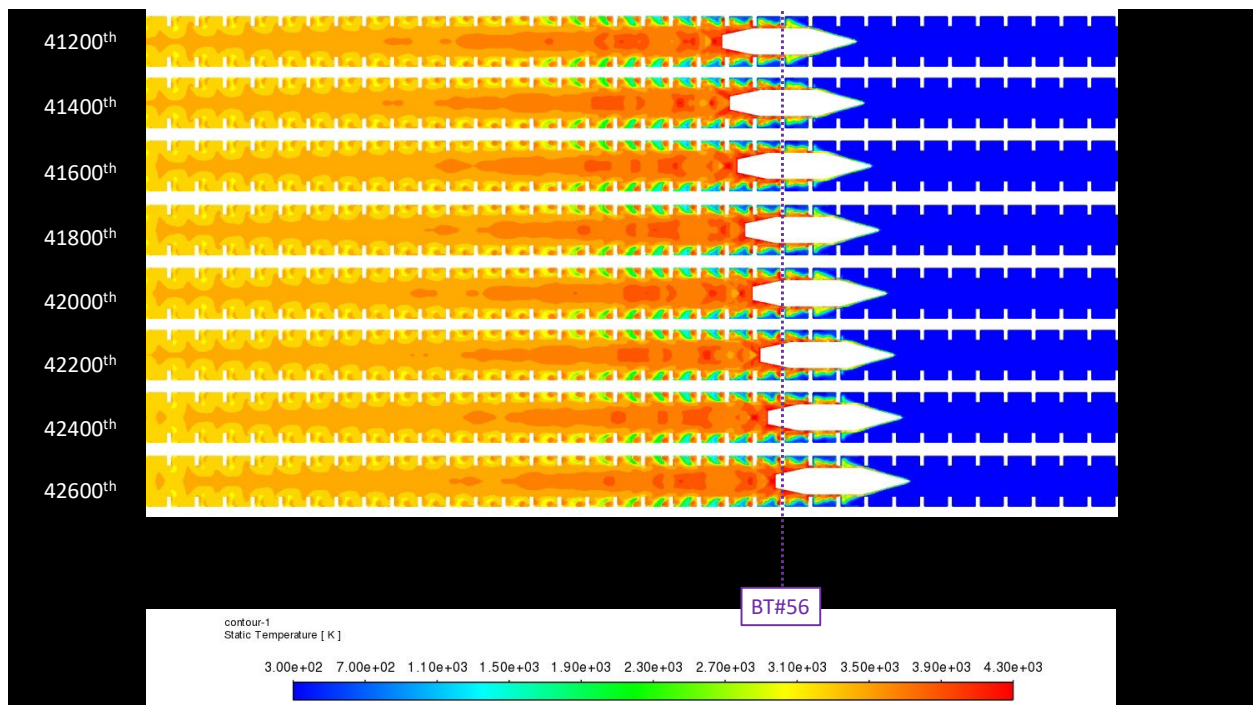


Figure 119 static temperature of P380-2B-12-15 inside BTRA501 at 8000g constant acceleration near Baffle#56

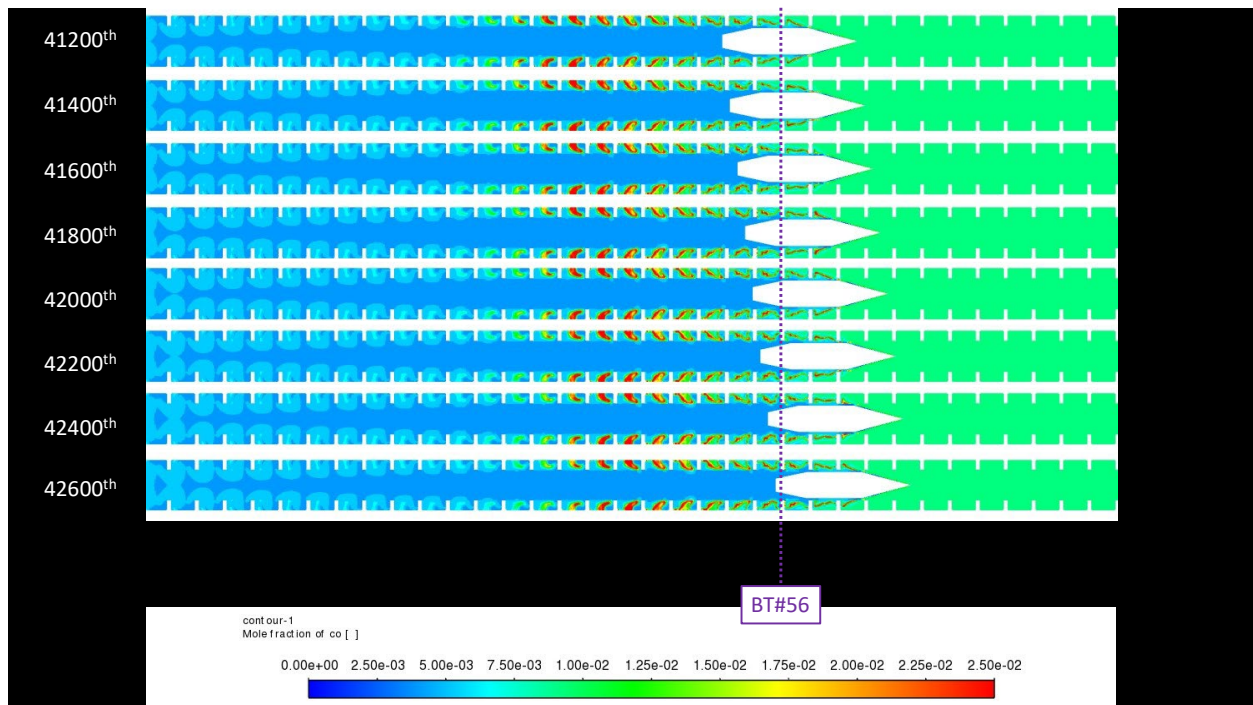


Figure 120 CO-mole fraction of P380-2B-12-15 inside BTRA501 at 8000g constant acceleration near Baffle#56

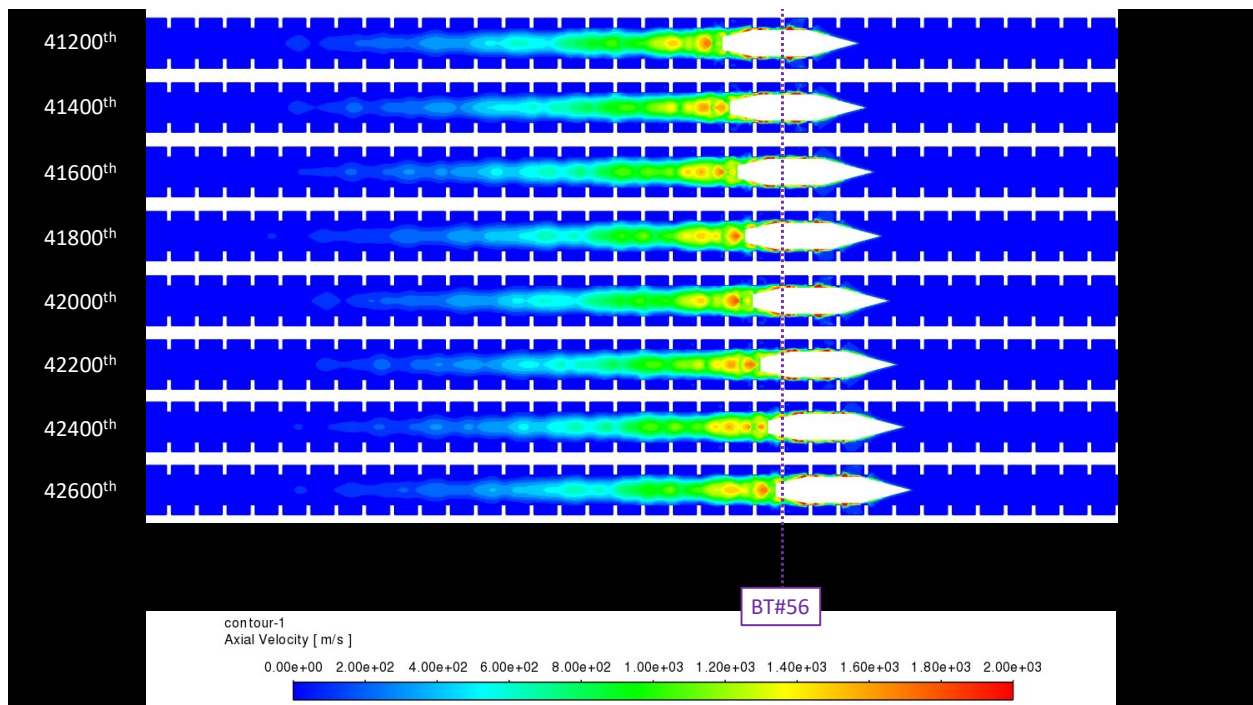


Figure 121 axial velocity of P380-2B-12-15 inside BTRA501 at 8000g constant acceleration near Baffle#56

3.7.2 P380-2B-12-15 with 19656g Constant Acceleration (1.0 to 1.2 km/s)

The P380-2B-12-15 (short projectile) initially has a 4.2-unit non-dimensional thrust when it moves at a constant velocity of 1.0 km/s inside BTRA501 configuration until 18750th time step. Then, projectile starts to accelerate with 19656g and it reaches a maximum 5.1-unit non-dimensional thrust around 27500th time step when the projectile velocity is around 1068 m/s. Then, the non-dimensional thrust decreases to around 4.0-unit around 44800th time step. The drag contribution from the nose cone starts around -3.0-unit and remains relatively constant even when the projectile accelerates. The thrust contribution from the base and tail of the projectile follow the total thrust trend. The base shows thrust fluctuation increase initially, but it reduces toward the end of the simulation (higher velocity near 1.2 km/s). While, the tail a larger thrust fluctuation initially and then the fluctuation reduces toward the end of the simulation. Overall, the 19656g accelerated cases barely reaches a quasi-periodic solution at the last 10% of the simulation. The non-dimensional thrust toward the end of the simulation, i.e., near 1.2 km/s, is very similar to that of the constant velocity of 1.2 km/s case. The same observation was made for the previous accelerated case, i.e., accelerating at 800g from 1.0 to 1.1 km/s. The thrust performance of the short projectile with 19656g acceleration is shown in Figure 122. The static pressure, static temperature, CO-mole fraction, and the axial velocity fields are shown during 42800th to 44200th time step in Figure 123, Figure 124, Figure 125, and Figure 126 accordingly. Note that the velocity of the projectile is about 1184 m/s at 42800th time step and about 1195 m/s at 44200th time step accordingly.

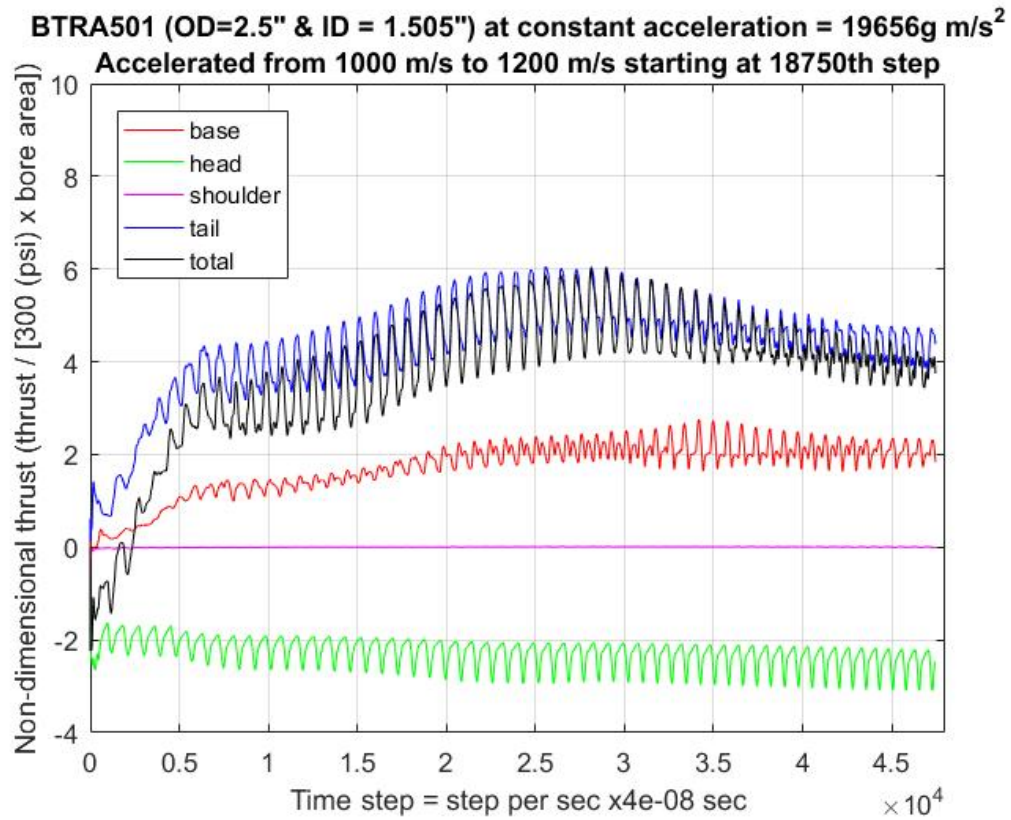


Figure 122 non-dimensional thrust breakdown of P380-2B-12-15 inside BTRA501 at 19656g constant acceleration (1.0 to 1.2 km/s)

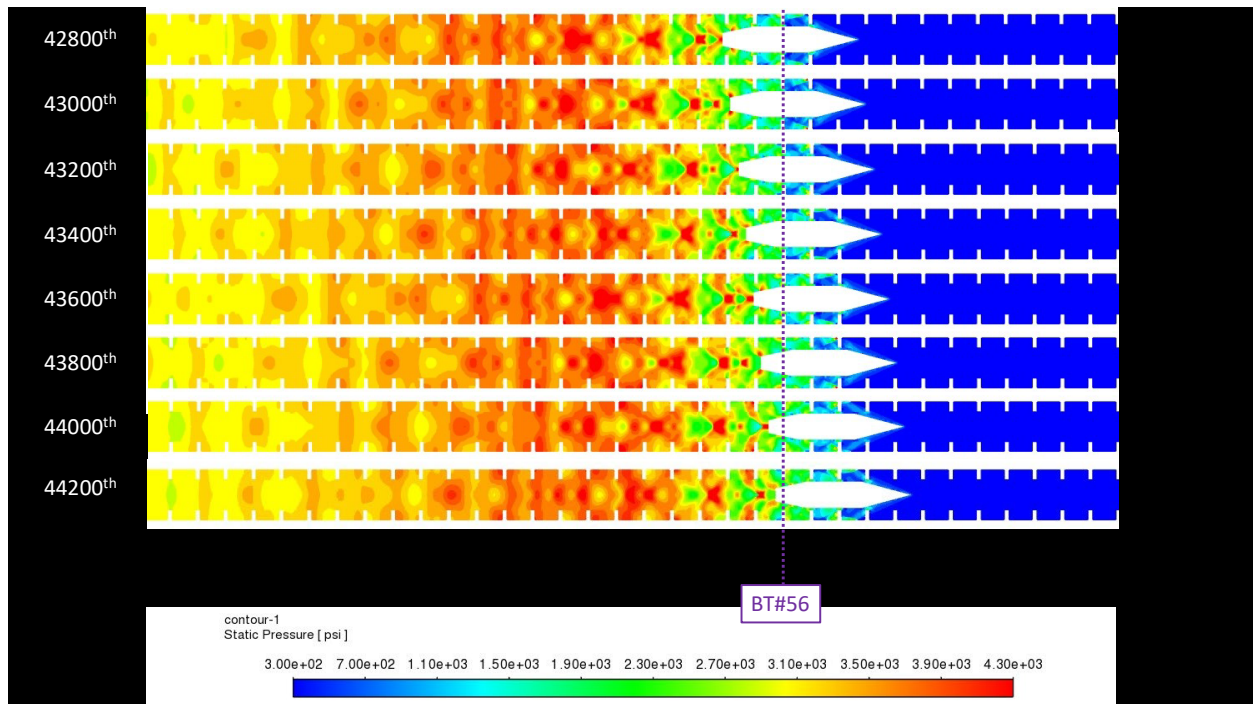


Figure 123 static pressure of P380-2B-12-15 inside BTRA501 at 19656g constant acceleration near Baffle#56

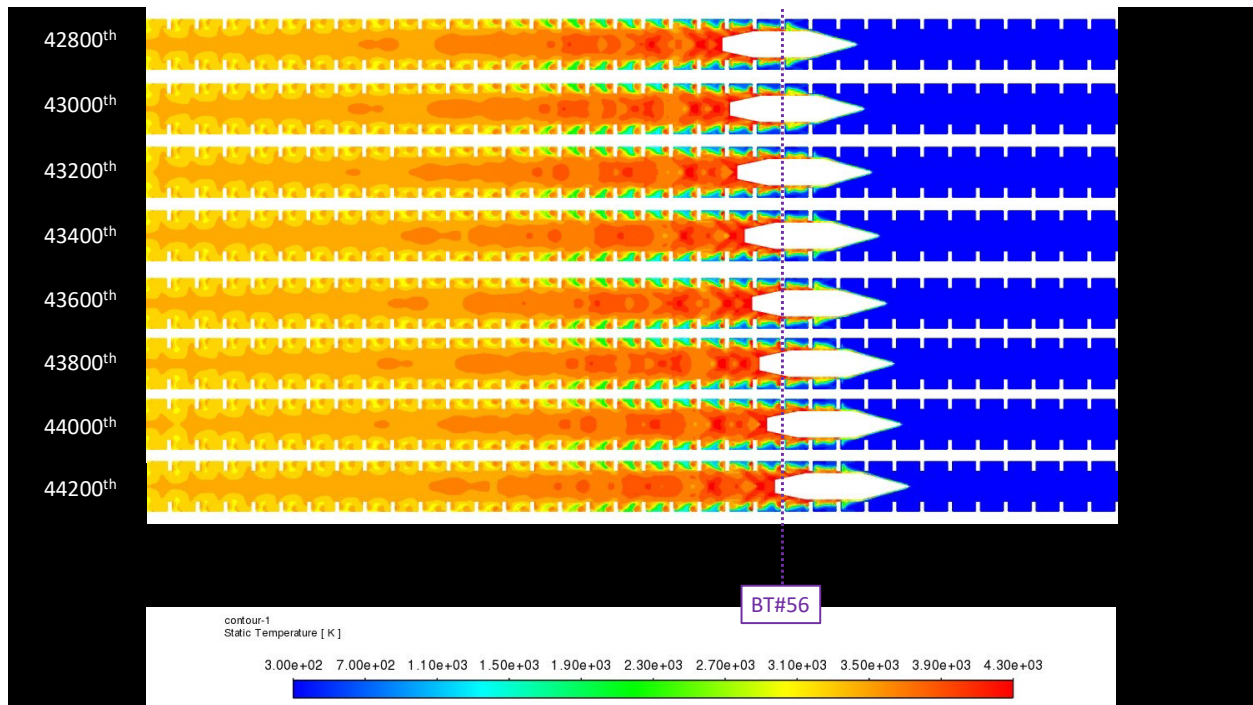


Figure 124 static temperature of P380-2B-12-15 inside BTRA501 at 19656g constant acceleration near Baffle#56

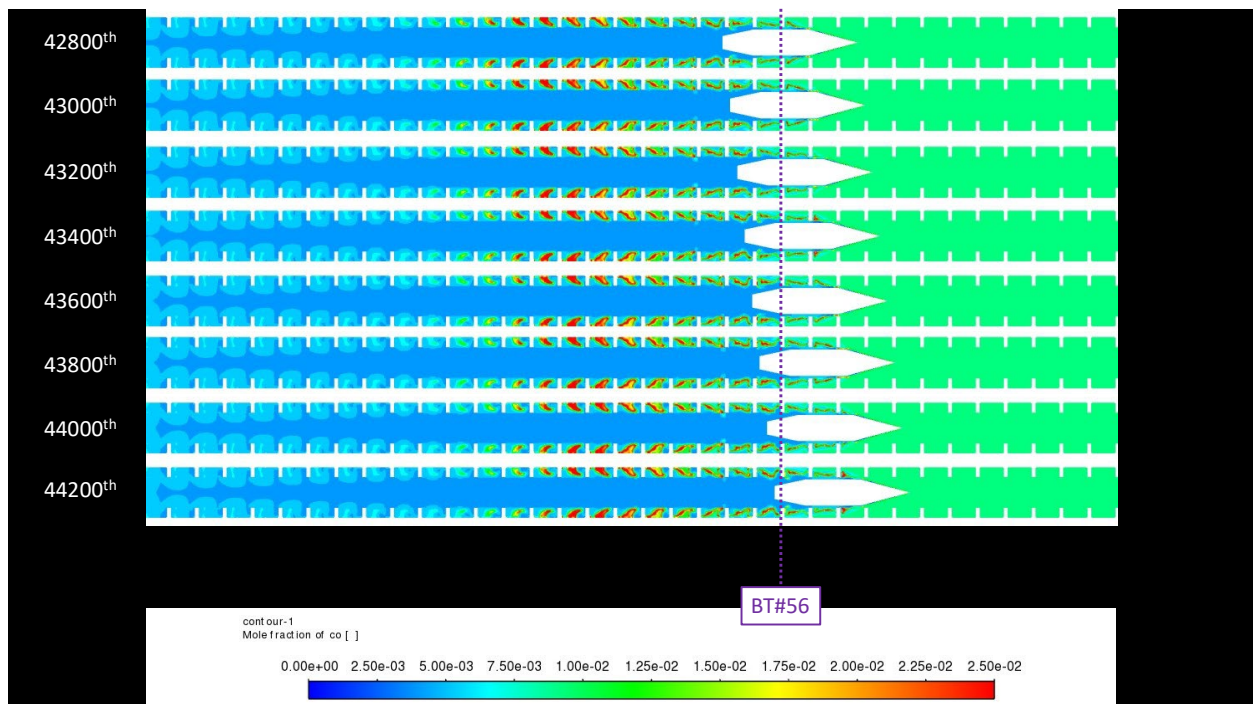


Figure 125 CO-mole fraction of P380-2B-12-15 inside BTRA501 at 19656g constant acceleration near Baffle#56

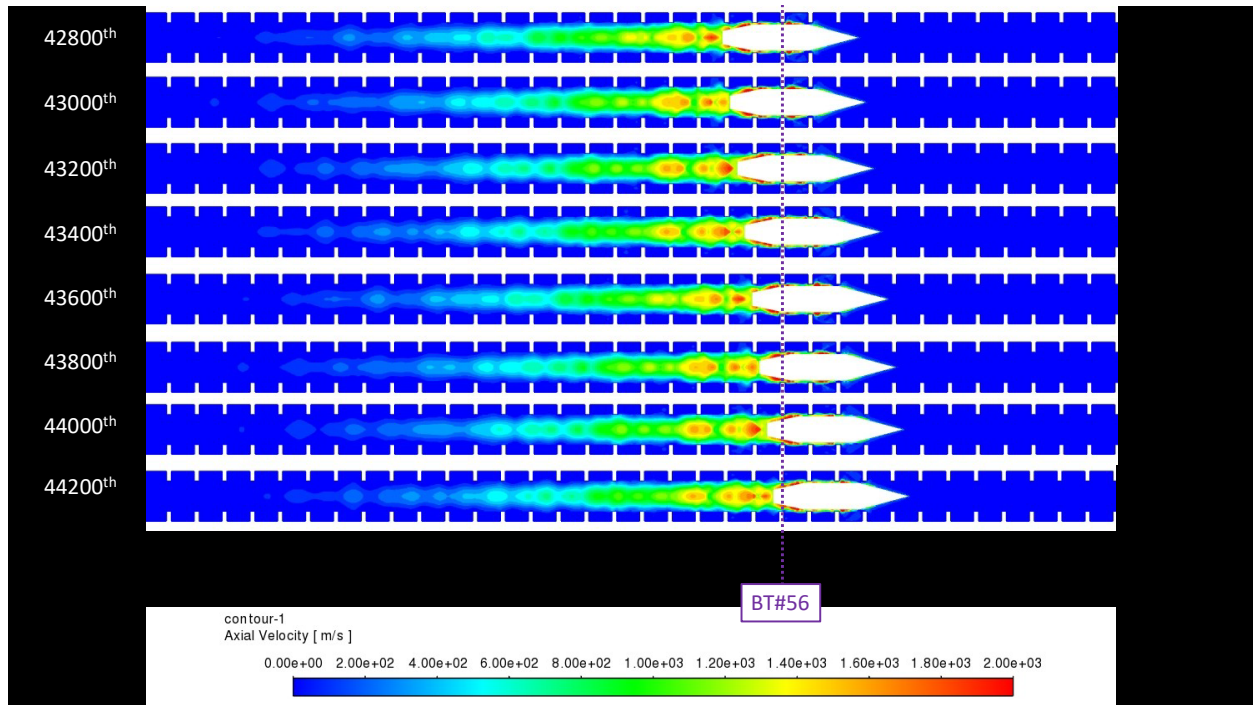


Figure 126 axial velocity of P380-2B-12-15 inside BTRA501 at 19656g constant acceleration near Baffle#56

3.7.3 P380-3B-12-15 with 19656g Constant Acceleration (1.0 to 1.2 km/s)

For P380-3B-12-15 (long projectile) initially has a 4.2-unit non-dimensional thrust when it moves at a constant velocity of 1.0 km/s inside BTRA501 configuration until 18750th time step. Then, projectile starts to accelerate with 19656g and it reaches a maximum 5.1-unit non-dimensional thrust around 27500th time step when the projectile velocity is around 1068 m/s. Then, the non-dimensional thrust decreases to around 4.0-unit around 44800th time step. The drag contribution from the nose cone starts around -3.0-unit and remains relatively constant even when the projectile accelerates. The thrust contribution from the base and tail of the projectile follow the total thrust trend. The base shows thrust fluctuation increase initially, but it reduces toward the end of the simulation (higher velocity near 1.2 km/s). While, the tail a larger thrust fluctuation initially and then the fluctuation reduces toward the end of the simulation. Overall,

the 19656g accelerated cases barely reaches a quasi-periodic solution at the last 10% of the simulation. The non-dimensional thrust toward the end of the simulation, i.e., near 1.2 km/s, is smaller by ~ 1 unit relative to that of the constant velocity of 1.2 km/s case (5.0 non-dimensional thrust). The observation is dissimilar to what was observed for the previous accelerated case, i.e., accelerating at 19656g from 1.0 to 1.2 km/s. The thrust performance of the long projectile with 19656g acceleration is shown in Figure 127. The static pressure, static temperature, CO-mole fraction, and the axial velocity fields are shown during 42800th to 44200th time step in Figure 128, Figure 129, Figure 130, and Figure 131 accordingly. Note that the velocity of the projectile is about 1184 m/s at 42800th time step and about 1195 m/s at 44200th time step accordingly.

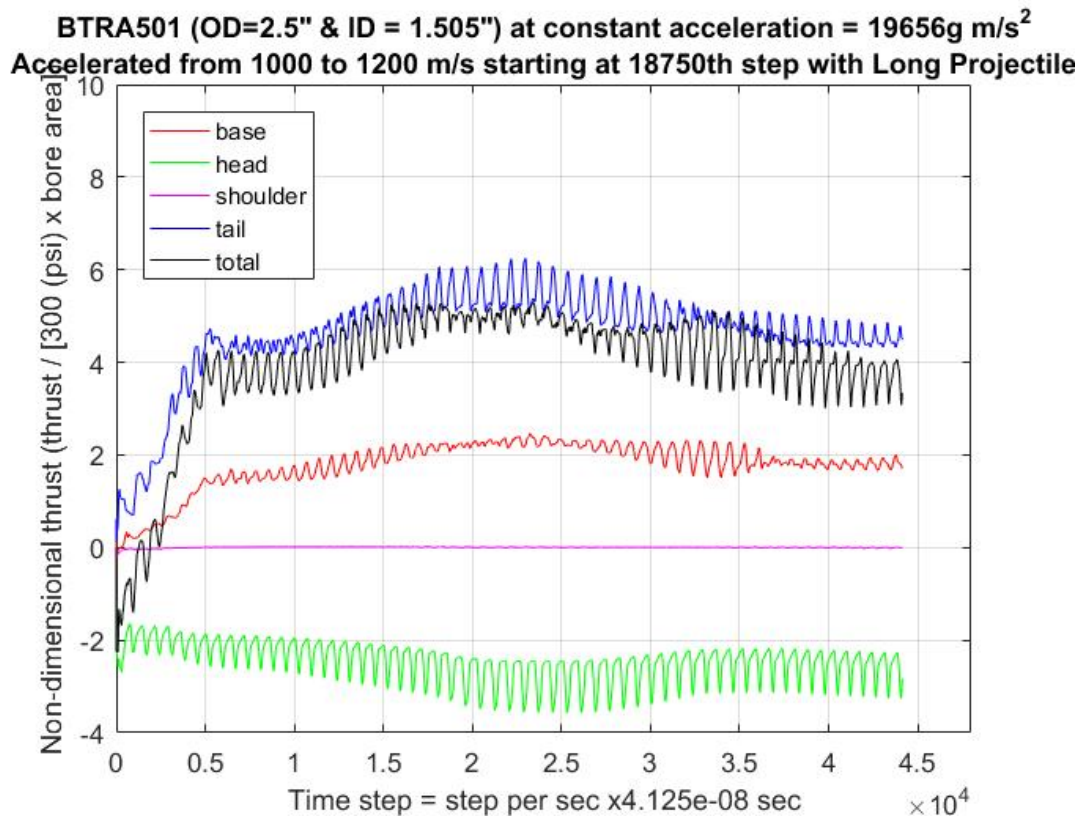


Figure 127 non-dimensional thrust breakdown of P380-3B-12-15 inside BTRA501 at 19656g constant acceleration (1.0 to 1.2 km/s)

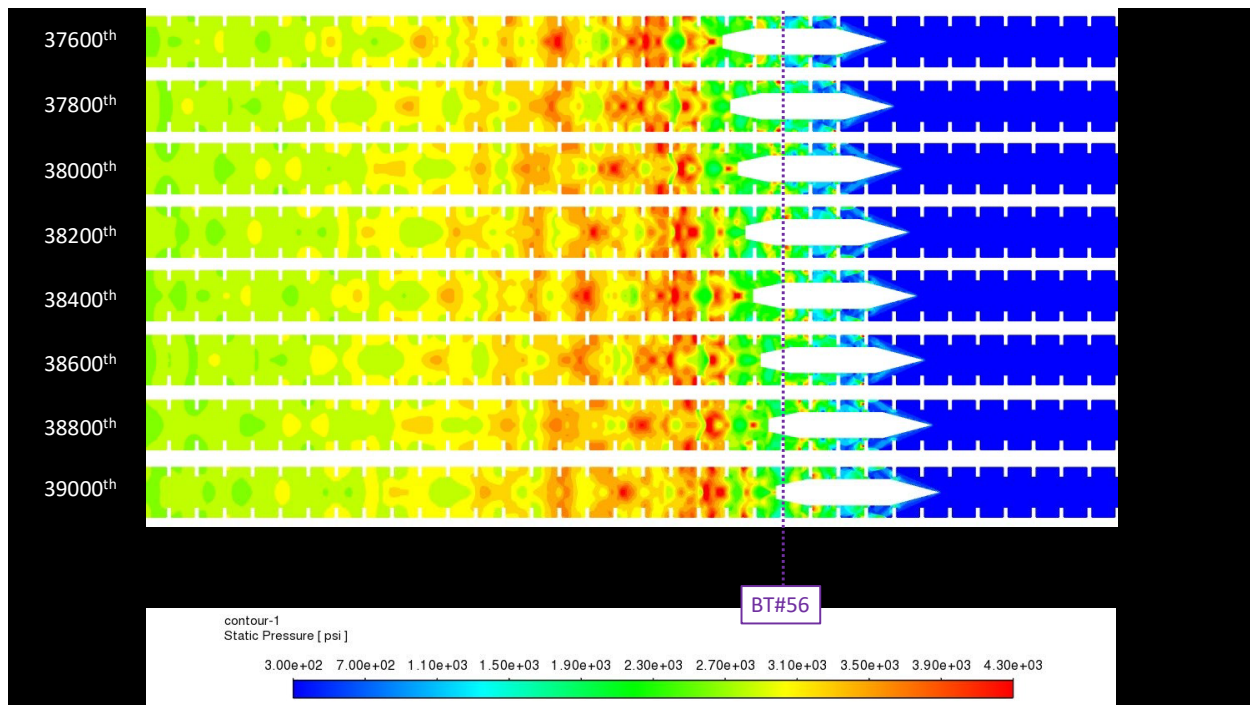


Figure 128 static pressure of P380-3B-12-15 inside BTRA501 at 19656g constant acceleration near Baffle#56

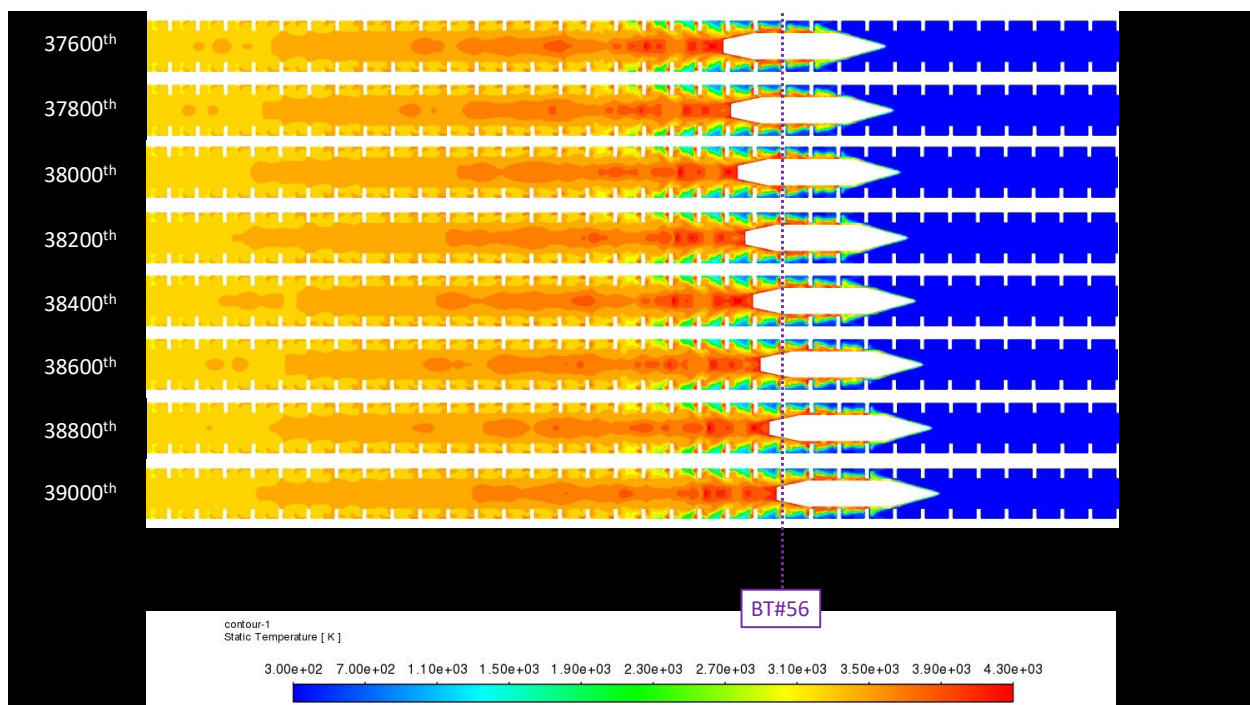


Figure 129 static temperature of P380-3B-12-15 inside BTRA501 at 19656g constant acceleration near Baffle#56

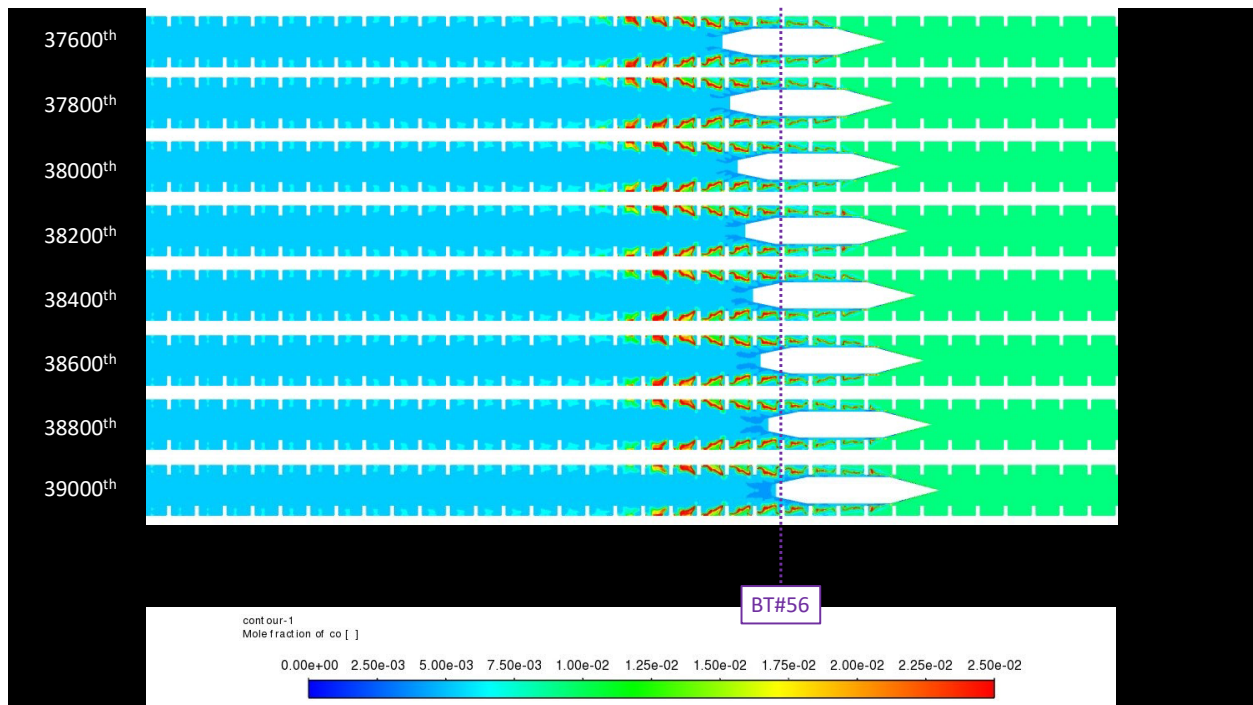


Figure 130 CO-mole fraction of P380-3B-12-15 inside BTRA501 at 19656g constant acceleration near Baffle#56

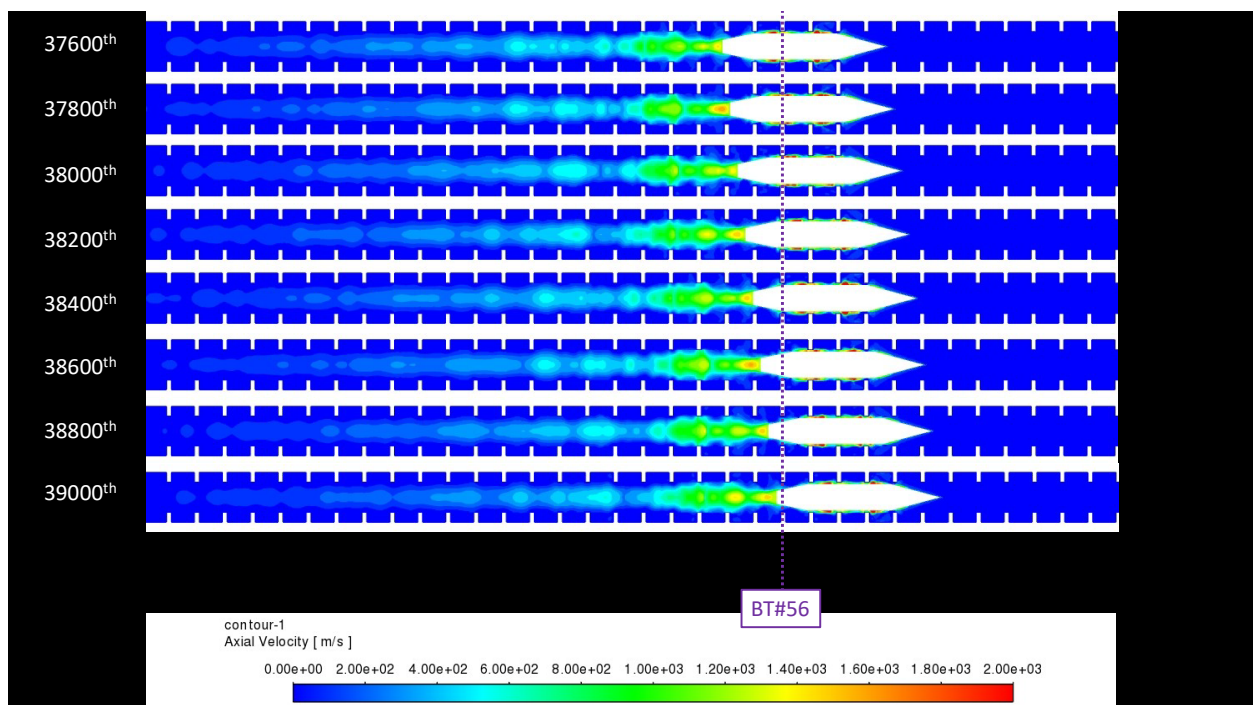


Figure 131 axial velocity of P380-3B-12-15 inside BTRA501 at 19656g constant acceleration near Baffle#56

3.7.4 P380-2B-12-15 with 8000g and 19656g Constant Acceleration (1.0 to 1.1 km/s, and 1.0 to 1.2 km/s) vs. P380-3B-12-15 with 19656g Constant Acceleration (1.0 to 1.2 km/s) Discussion

The non-dimensional thrust of P380-2B-12-15 moving from 1.0 km/s, 1.1 km/s and from 1.0 to 1.1 km/s with 8000g acceleration BTRA501 appended with the static pressure fields and CO-mole fraction are shown in Figure 132 and Figure 133 accordingly. In all three cases, the thrust contribution from the tail of projectile is larger than that of the base due to its larger projected area. Also, when maximum peak thrust on the base is realized, it coincides with minimum thrust on the tail and maximum drag force on the nose cone. Conversely, when the maximum peak thrust on the tail is realized, it coincides with minimum thrust on the base and minimum drag on the nosecone in all three cases. The nose cone only generates drag and its peak drag contribution arises every time the nose-shoulder joint passes through the hole in a baffle, which coincides with the rear edge of the two-baffle-insert-length projectile shoulder entering a baffle hole too. The net thrust reaches a quasi-periodic state on constant velocity cases at latter part of the simulations, while the 8000g acceleration does not show that. However, the 8000g accelerated case roughly reaches the same non-dimensional thrust toward the end of the simulation as the constant velocity of 1.1 km/s case, i.e., the non-dimensional thrust roughly is about 5.0-unit. The instantaneous static pressure and CO-mole fraction fields are more similar in the 1.1 km/s and 8000g accelerated cases. In general, the high-pressure region is located behind the base in 1.0 km/s case. While, there is some gap between the high-pressure region for 1.1 km/s and 8000g accelerated case and that is why the non-dimensional thrust is lower relative to 1.0 km/s. The CO-mole fraction field comparison shows that large amount of CO is created and consumed behind the base projectile in 1.0 km/s case. While, a larger trace of CO stretches further downstream in

1.1 km/s and 8000g accelerated case showing less efficient combustion and heat release in those cases.

BTRA501 with P380-2B-12-15 (short projectile) non-dimensional thrust and static pressure flow field at 1000 m/s (Left) vs. 1100 m/s (Center) vs. 8000g m/s² from 1000 to 1100 m/s (Right)

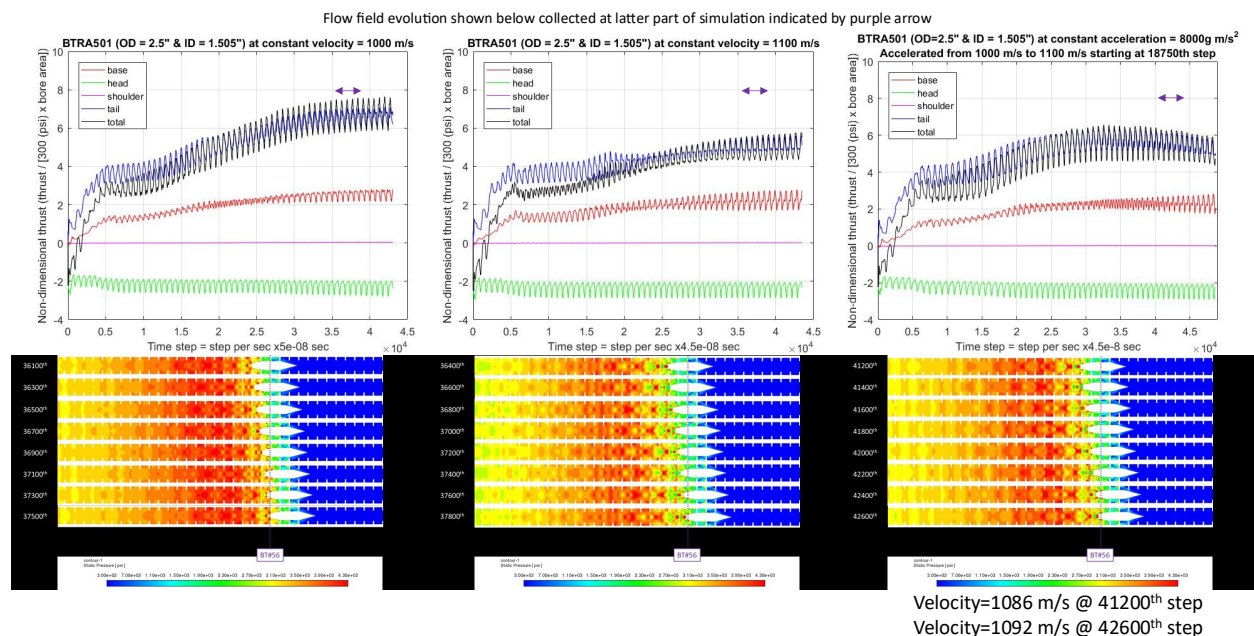


Figure 132 static pressure field of P380-2B-12-15 in BTRA501 at 1.0 km/s vs. 1.1 km/s vs. 1.0-to-1.1 km/s at 8000g

BTRA501 with P380-2B-12-15 (short projectile) non-dimensional thrust and CO-mol fraction flow field at 1000 m/s (Left) vs. 1100 m/s (Center) vs. 8000g m/s² from 1000 to 1100 m/s (Right)

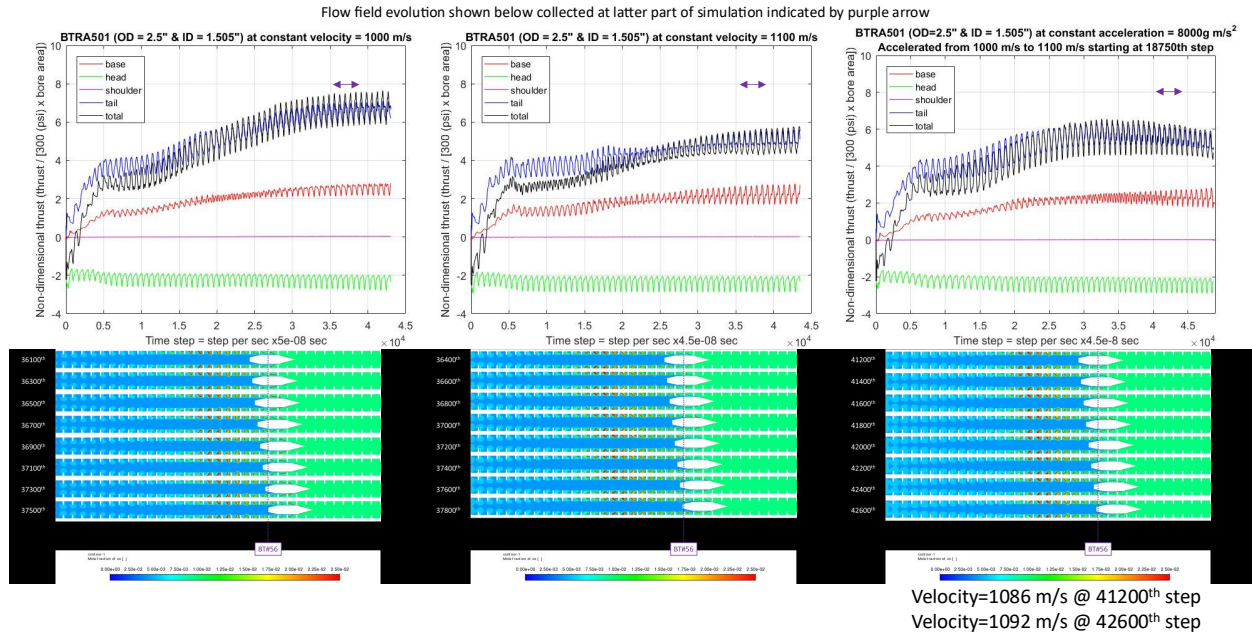


Figure 133 CO-mole fraction field of P380-2B-12-15 in BTRA501 at 1.0 km/s vs. 1.1 km/s vs. 1.0-to-1.1 km/s at 8000g

The non-dimensional thrust of P380-2B-12-15 moving from 1.0 km/s, 1.2 km/s and from 1.0 to 1.2 km/s with 19656g acceleration BTRA501 appended with the static pressure fields and CO-mole fraction are shown in Figure 134 and Figure 135 accordingly. In all three cases, the thrust contribution from the tail of projectile is larger than that of the base due to its larger projected area. Also, when maximum peak thrust on the base is realized, it coincides with minimum thrust on the tail and maximum drag force on the nose cone. Conversely, when the maximum peak thrust on the tail is realized, it coincides with minimum thrust on the base and minimum drag on the nosecone in all three cases. The nose cone only generates drag and its peak drag contribution arises every time the nose-shoulder joint passes through the hole in a baffle, which coincides with the rear edge of the two-baffle-insert-length projectile shoulder entering a baffle hole too. The

net thrust reaches a quasi-periodic state for all three cases toward the end of the simulations. The 19656g accelerated case roughly reaches the same non-dimensional thrust toward the end of the simulation as the constant velocity of 1.2 km/s case, i.e., the non-dimensional thrust roughly is about 4.0-unit. The instantaneous static pressure and CO-mole fraction fields are more similar in the 1.2 km/s and 19656g accelerated cases. In general, the high-pressure region is located behind the base in 1.0 km/s case. While, there is some gap between the high-pressure region for 1.2 km/s and 19656g accelerated case and that is why the non-dimensional thrust is lower relative to 1.0 km/s. The CO-mole fraction field comparison shows that large amount of CO is created and consumed behind the base projectile in 1.0 km/s case. While, a larger trace of CO stretches further downstream in 1.2 km/s and 19656g accelerated case showing less efficient combustion and heat release in those cases.

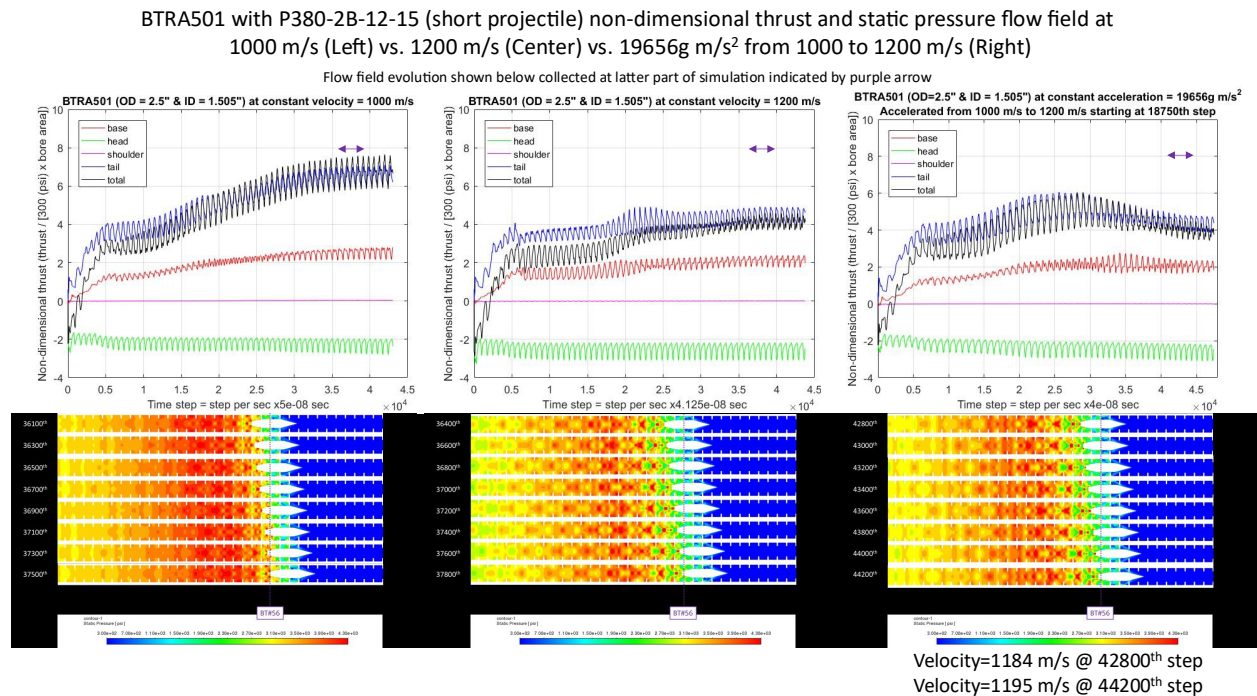


Figure 134 static pressure field of P380-2B-12-15 in BTRA501 at 1.0 km/s vs. 1.2 km/s vs. 1.0-to-1.2 km/s at 19656g

BTRA501 with P380-2B-12-15 (short projectile) non-dimensional thrust and CO-mol fraction flow field at 1000 m/s (Left) vs. 1200 m/s (Center) vs. 19656g m/s² from 1000 to 1200 m/s (Right)

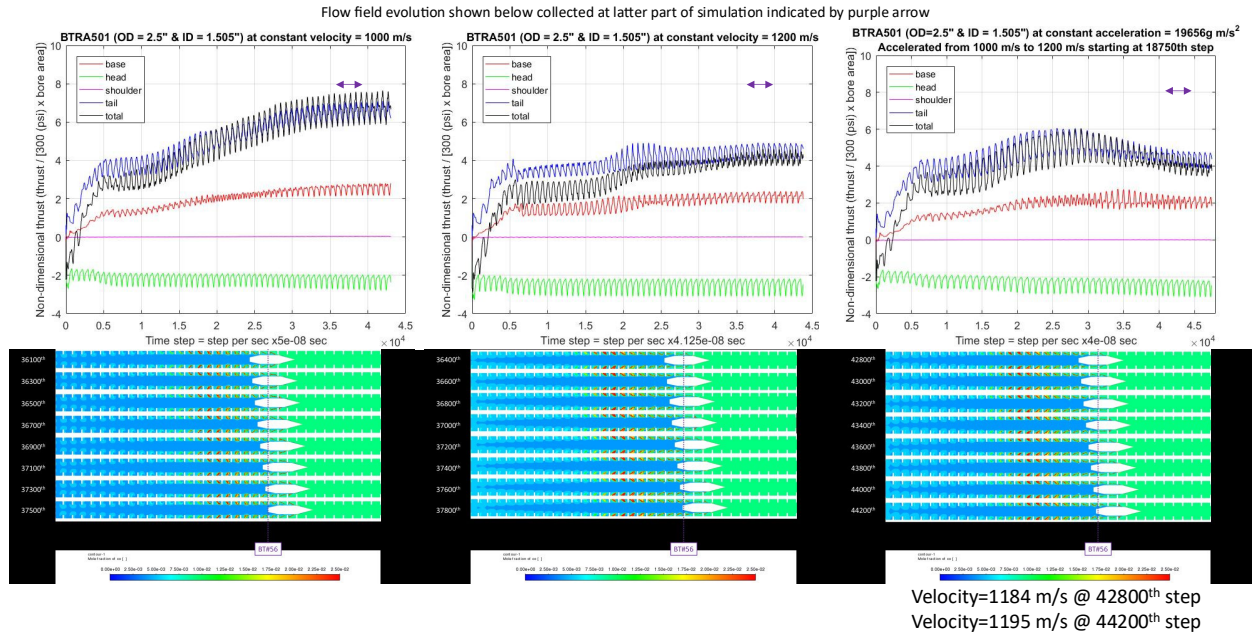


Figure 135 CO-mole fraction field of P380-2B-12-15 in BTRA501 at 1.0 km/s vs. 1.2 km/s vs. 1.0-to-1.2 km/s at 19656g

The non-dimensional thrust of P380-3B-12-15 (long projectile) moving from 1.0 km/s, 1.2 km/s and from 1.0 to 1.2 km/s with 19656g acceleration BTRA501 appended with the static pressure fields and CO-mole fraction are shown in Figure 136 and Figure 137 accordingly. The projectile unstarts at 1.0 km/s while it remains started at 1.2 km/s constant velocities. When the long projectile accelerates at 19656g, it shows an unstart behavior first. But when the projectile goes to a higher velocity, the flow recovers over the nose cone and it remains started throughout the simulation when the projectile reaches 1.2 km/s. However, the non-dimensional thrust of the accelerated case when the projectile reaches 1.2 km/s is smaller than that of the constant 1.2 km/s case. It is speculated that a longer domain is required to observe and confirm if the non-dimensional thrust increase and reaches a quasi-periodic solution or not. In all three cases, the

thrust contribution from the long projectile segments is similar to that of the short projectile cases. The net thrust reaches a quasi-periodic state for all three cases toward the end of the simulations. The 19656g accelerated case roughly reaches lower non-dimensional thrust (3.8-unit) toward the end of the simulation relative to the constant velocity of 1.2 km/s case, i.e., the non-dimensional thrust roughly is about 5.0-unit. The instantaneous static pressure and CO-mole fraction fields are more similar in the 1.2 km/s and 19656g accelerated cases. In general, the high-pressure region is located behind the base in 1.0 km/s case. While, there is some gap between the high-pressure region for 1.2 km/s and 19656g accelerated case and that is why the non-dimensional thrust is lower relative to 1.0 km/s. The CO-mole fraction field comparison shows that large amount of CO is created and consumed behind the base projectile in 1.0 km/s case. While, a larger trace of CO stretches further downstream in 1.2 km/s and 19656g accelerated case showing less efficient combustion and heat release in those cases.

BTRA501 with P380-3B-12-15 (long projectile) non-dimensional thrust and static pressure flow field at 1000 m/s (Left) vs. 1200 m/s (Center) vs. $\sim 19656g$ m/s² from 1000 to 1200 m/s (Right)

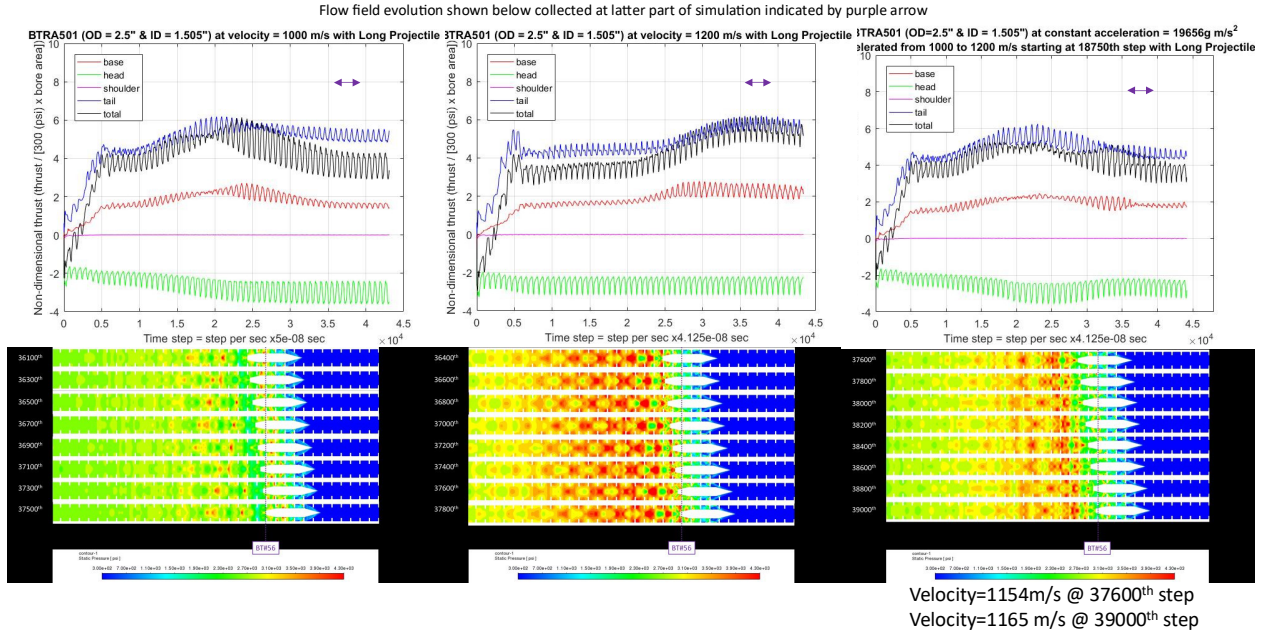


Figure 136 static pressure field of P380-3B-12-15 in BTRA501 at 1.0 km/s vs. 1.2 km/s vs. 1.0-to-1.2 km/s at 19656g

BTRA501 with P380-3B-12-15 (long projectile) non-dimensional thrust and CO-mol fraction flow field at 1000 m/s (Left) vs. 1200 m/s (Center) vs. $\sim 19656g$ m/s² from 1000 to 1200 m/s (Right)

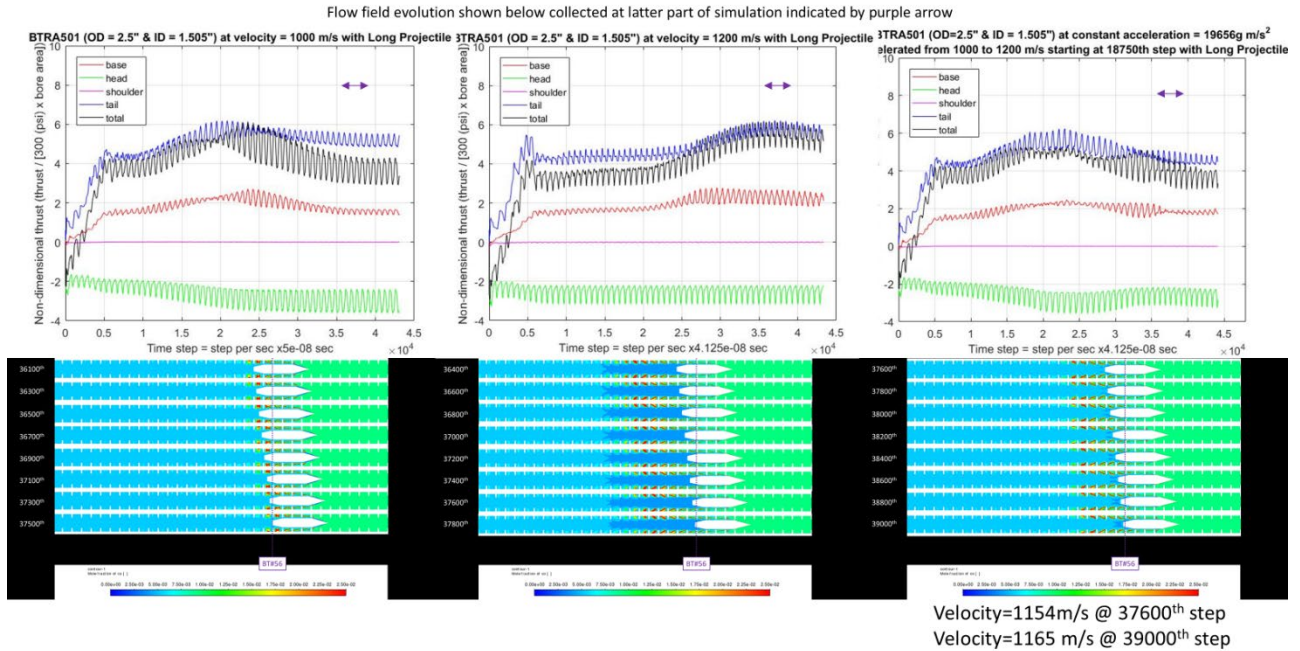


Figure 137 CO-mole fraction field of P380-3B-12-15 in BTRA501 at 1.0 km/s vs. 1.2 km/s vs. 1.0-to-1.2 km/s at 19656g

3.8 Determining Thermally Choked Region and Thrust Efficiency

The last goal of CFD simulations for this research study is to analytically estimate the location of thermally choked region behind the projectile when it moves at a constant velocity. This method allows to compute how kinetic and chemical energy is used to move the projectile and compare that with what is used to move the baffle tube in form of baffle drag. In other word, the goal is to identify the ratio of the projectile thrust normalized by the sum of baffle drag and projectile thrust. The methodology and rationale of estimating the thermally choked section at constant velocity and thrust efficiency are provided in Section 3.4 (3.4 CFD Modeling of BTRA and Available Data). Some results for the short projectile at various BTRA configurations and different velocities are presented in this section.

Using the definition of event#1 that is finding the exact time step when any given baffle experiences the maximum push net force (i.e., the maximum net force pushing on walls of a chosen baffle in the same direction as the projectile moves), thermally choked location and thrust efficiency are calculated for the following cases using the P380-2B-12-15 (short projectile) summarized in Table 13. Note that for flow field visualization comparison, a few specific time step intervals were chosen to extract images for consistency that led to choose event#1 be around Baffle#56 thru Baffle#58. However, estimating thermally choked location can be used for any desired baffle if needed. Also, note that balancing the momentum equation with a constant acceleration needs additional terms to account for the effect of momentum accumulation between Station#1 and Station#2 to estimate the location of thermally choked section [18]. Figure 138 is identical to Figure 52 that shows the process of estimating the theoretical thermally choked section inside BTRA is shown here for completeness.

Table 13 thermally choked location and thrust efficiency example for various BTRA configuration

Config.	Velocity (km/s)	Event#1 @ BT#	Base @ BT#	Thermally Choked @ BT#	Thrust efficiency
BTRA111	1.0	37510 th @ BT58	BT56	BT41	31%
BTRA501	1.0	37187 th @ BT58	BT55	BT45	62%
BTRA111-to-501	1.0	36923 th @ BT58	BT55	BT38	64%
BTRA501	1.2	37245 th @ BT56	BT55	BT43	38%
BTRA501	1.4	37624 th @ BT56	BT56	BT35	35%

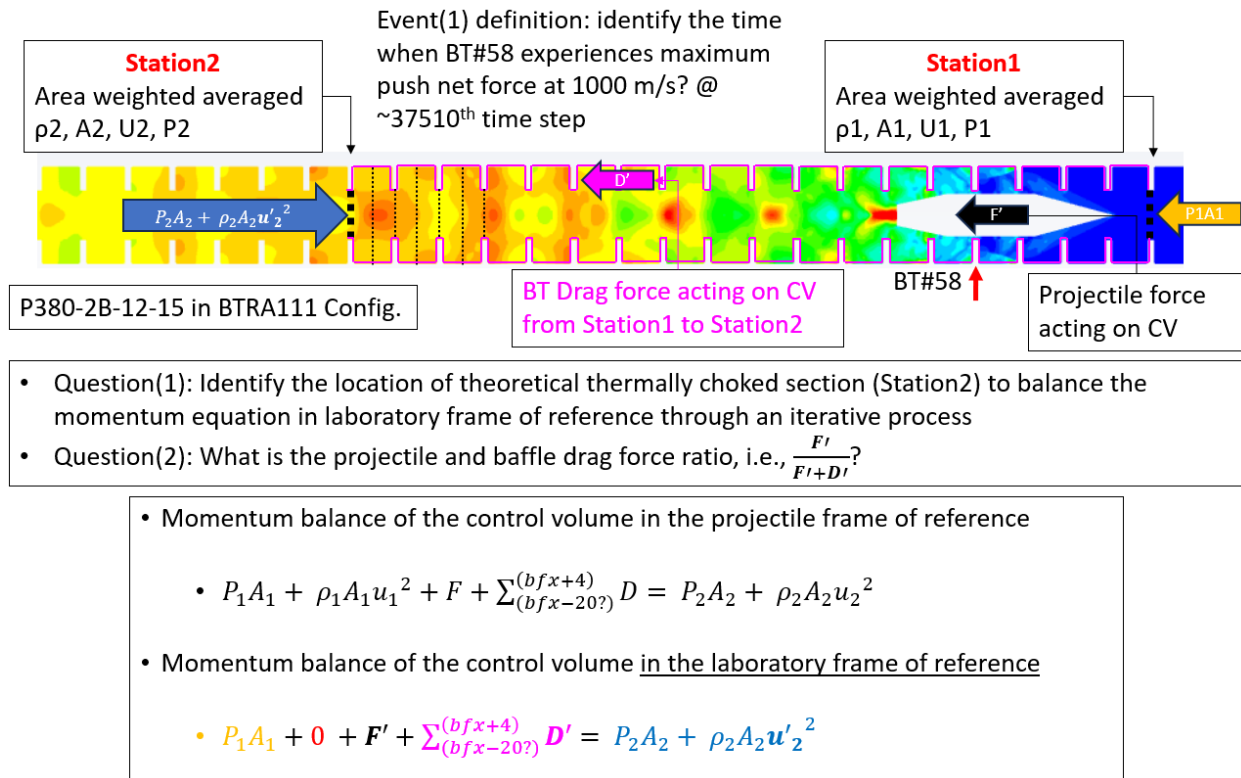


Figure 138 the process to estimate theoretical thermally choked section inside BTRA

When projectile moves at 1.0 km/s inside BTRA111, Baffle#58 experiences event#1, i.e., maximum push net force, at 37510th times step (5e-8 second per time step) when the shoulder of the projectile seals against Baffle#58. At this time, non-dimensional force acting on the Baffle#58 (normalized by fill pressure and bore area) is about 9.6-unit. In comparison, the non-dimensional thrust of the projectile at event#1 is about 3.4-unit. The balancing momentum equation process described in Figure 138 shows that the thermally choked region might be around Baffle#41 that is 15 baffles behind the projectile base with the thrust efficiency about 31%. The non-dimensional force acting on Baffle#58 and non-dimensional thrust breakdown on the projectile at event#1 are shown in Figure 139. The static pressure, static temperature, CO-mole fraction, and axial velocity fields at event#1 with estimated thermally choked section is shown in Figure 140. Lastly, balancing the momentum equation versus baffle location with static pressure contour plot is shown in Figure 141. Note that using this process to locate the thermally choked section by balancing the momentum equation is a first order estimate using a sparse data point. As a result, there should be an error bar associated with the momentum balance at each baffle location that has not been quantified yet that leads to potentially relocate the thermally choked section by a few baffles up or downstream.

Similar figures are shown for BTRA 501 at 1.0 km/s in Figure 142, Figure 143, and Figure 144; for BTRA111-to-501 at 1.0 km/s in Figure 145, Figure 146, and Figure 147; for BTRA501 at 1.2 km/s in Figure 148, Figure 149, and Figure 150; and for BTRA501 at 1.4 km/s in Figure 151, Figure 152, and Figure 153 accordingly. The explanations for these figures are similar to that of what is described above for BTRA111 case, but not explicitly described here to avoid repetition.

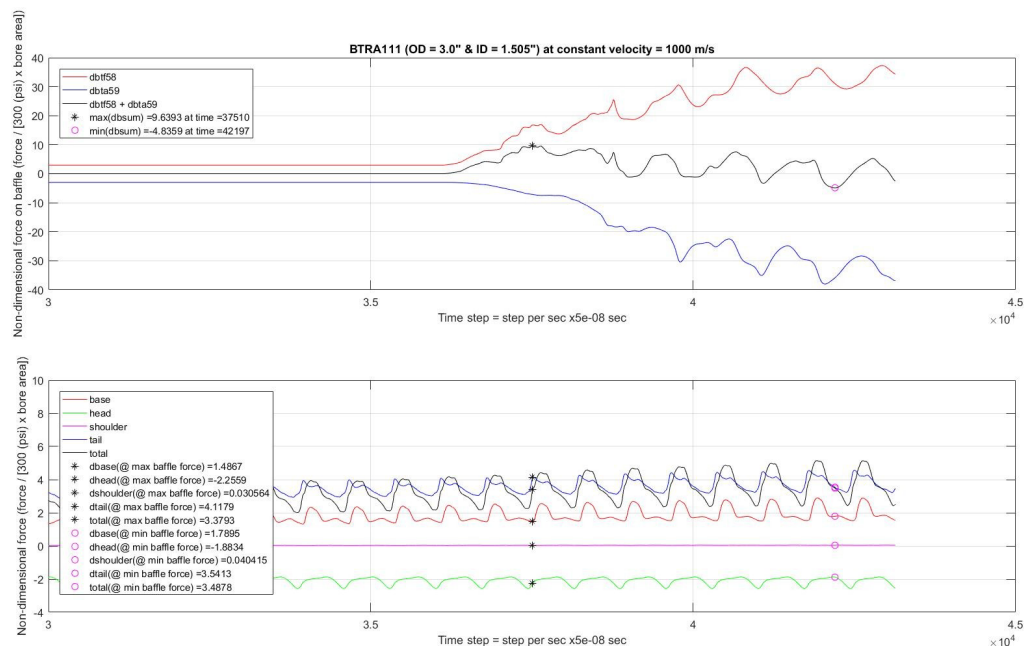


Figure 139 non-dimensional force signal on Baffle#58 in BTR111 and non-dimensional thrust breakdown on P380-2B-12-15 at 1.0 km/s

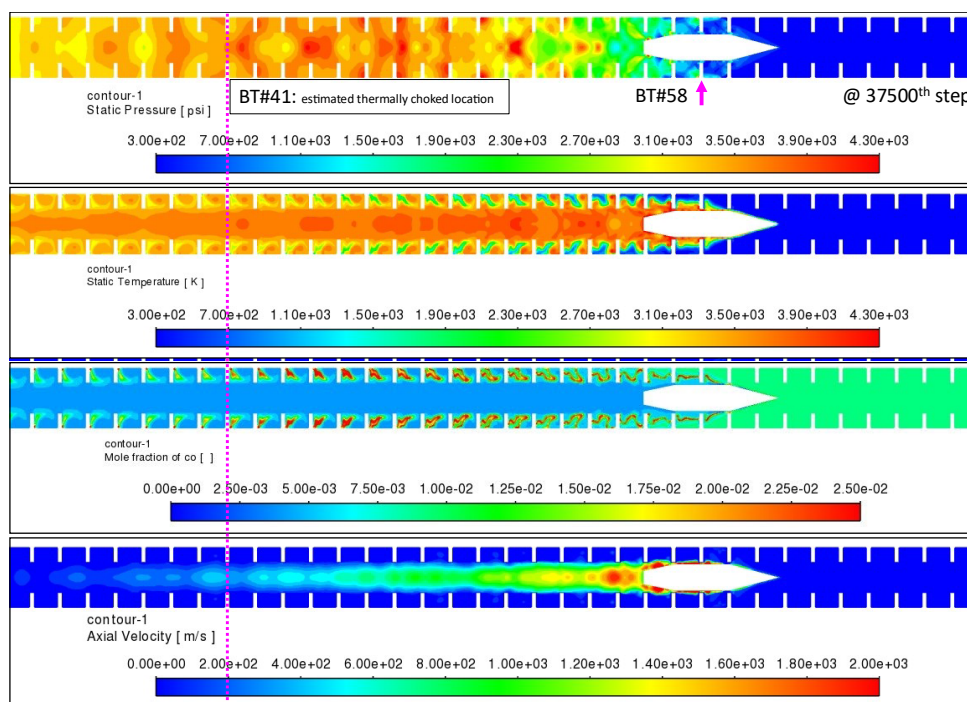


Figure 140 static-pressure, static-temperature, CO-mole fraction, and axial velocity maps of P380-2B-12-15 inside BTR111 at 1.0 km/s near BT#58 at approximately 37500th time step (5e-8 s per time step)

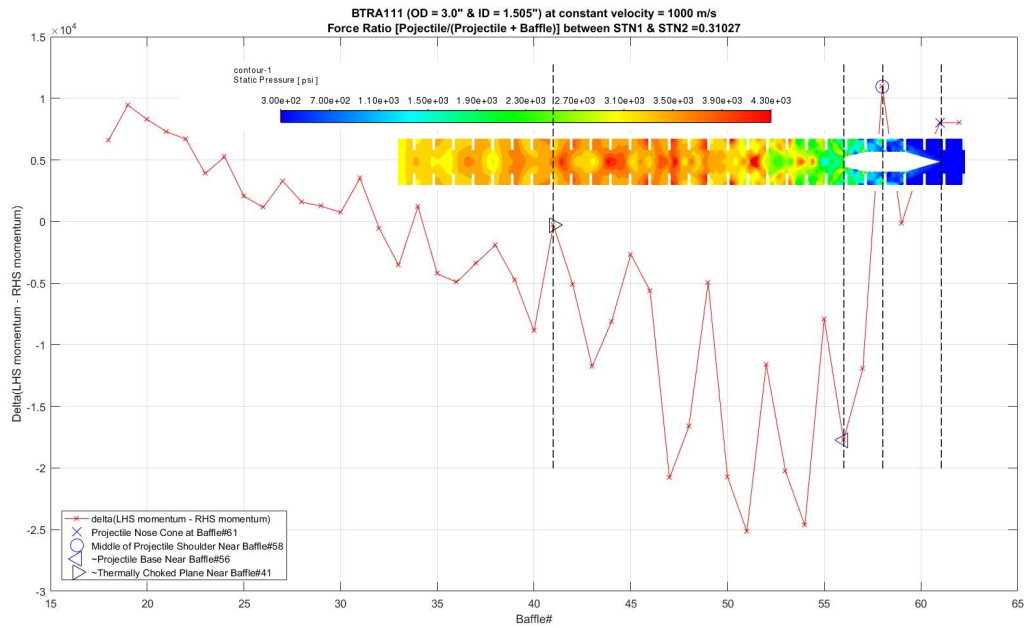


Figure 141 thermally choked location of P380-2B inside BTRA111 at 1.0 km/s and static pressure field

Figures below are associated with BTRA501 at 1.0 km/s case.

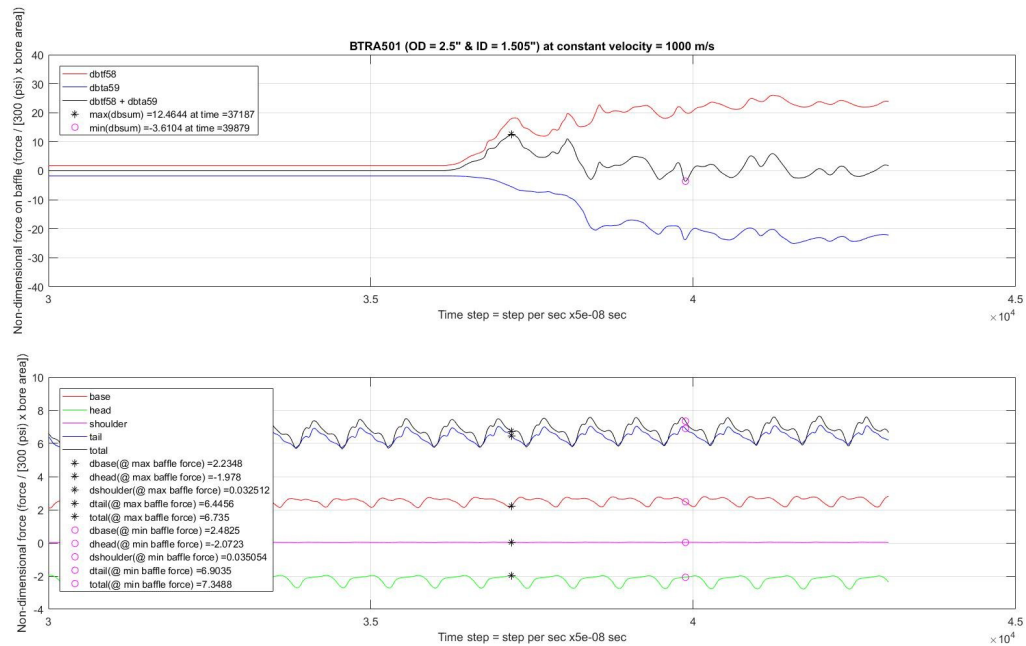


Figure 142 non-dimensional force signal on Baffle#58 in BTRA501 and non-dimensional thrust breakdown on P380-2B-12-15 at 1.0 km/s

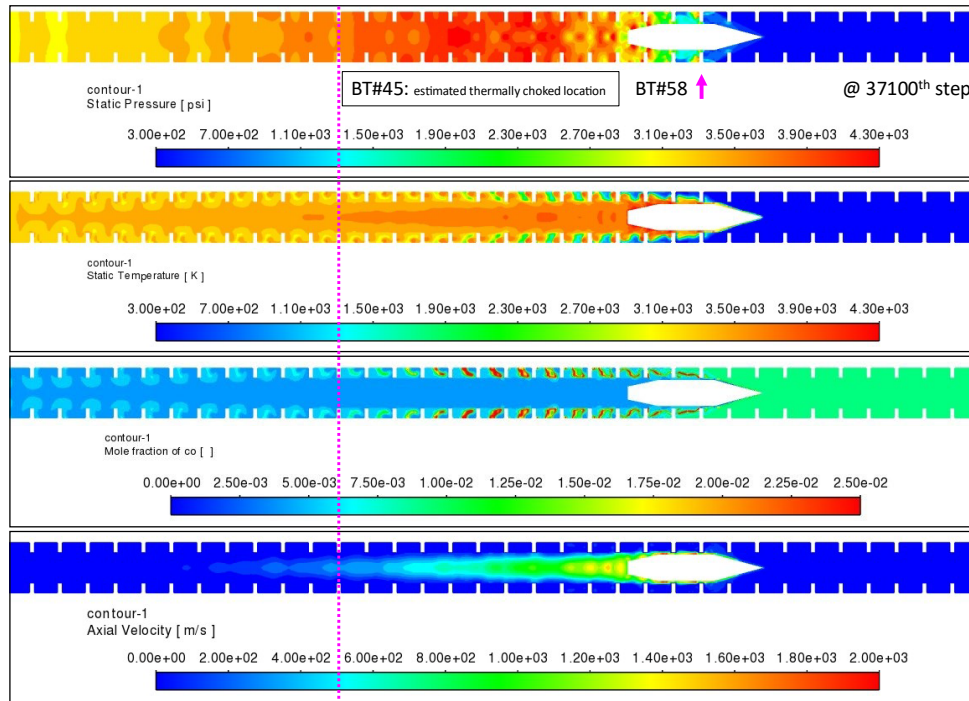


Figure 143 static-pressure, static-temperature, CO-mole fraction, and axial velocity maps of P380-2B-12-15 inside BTRA501 at 1.0 km/s near BT#58 at approximately 37100th time step (5e-8 s per time step)

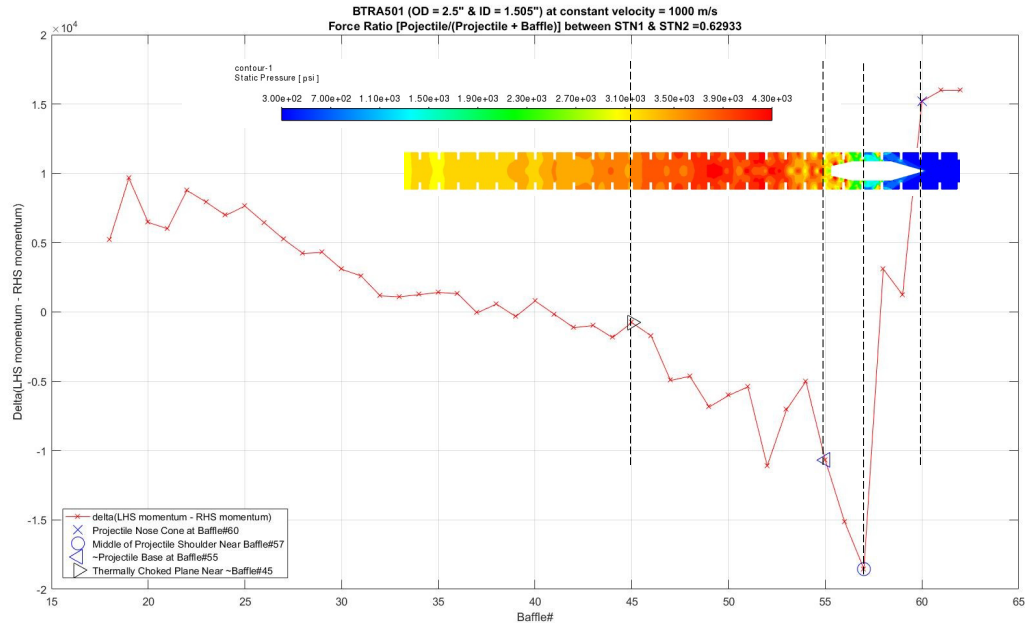


Figure 144 thermally choked location of P380-2B inside BTRA501 at 1.0 km/s and static pressure field

Figures below are associated with BTRA111-to-501 at 1.0 km/s case.

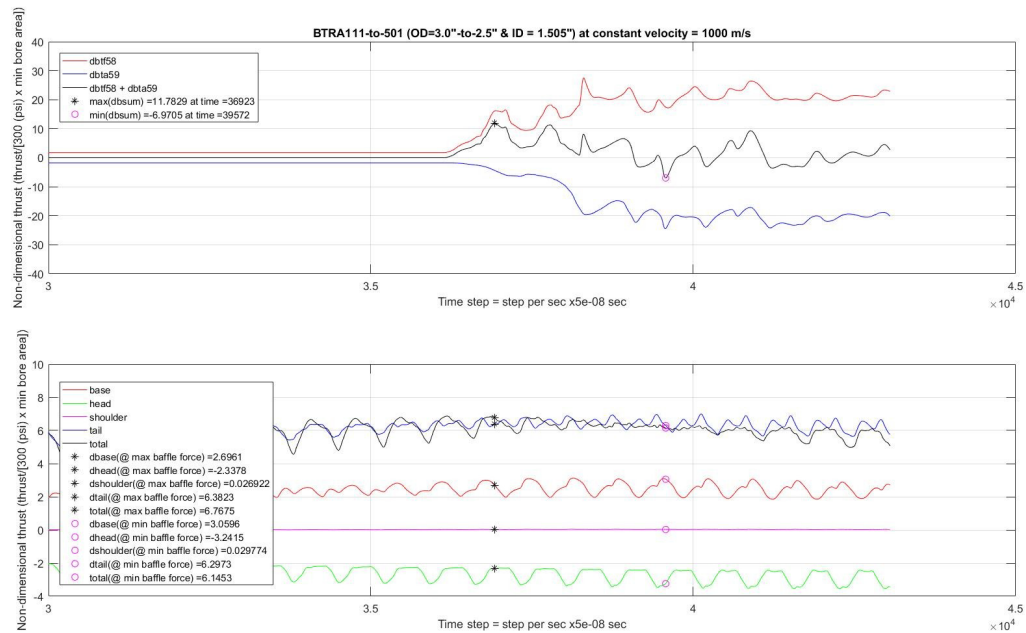


Figure 145 non-dimensional force signal on Baffle#58 in BTRA111-to-501 and non-dimensional thrust breakdown on P380-2B-12-15 at 1.0 km/s

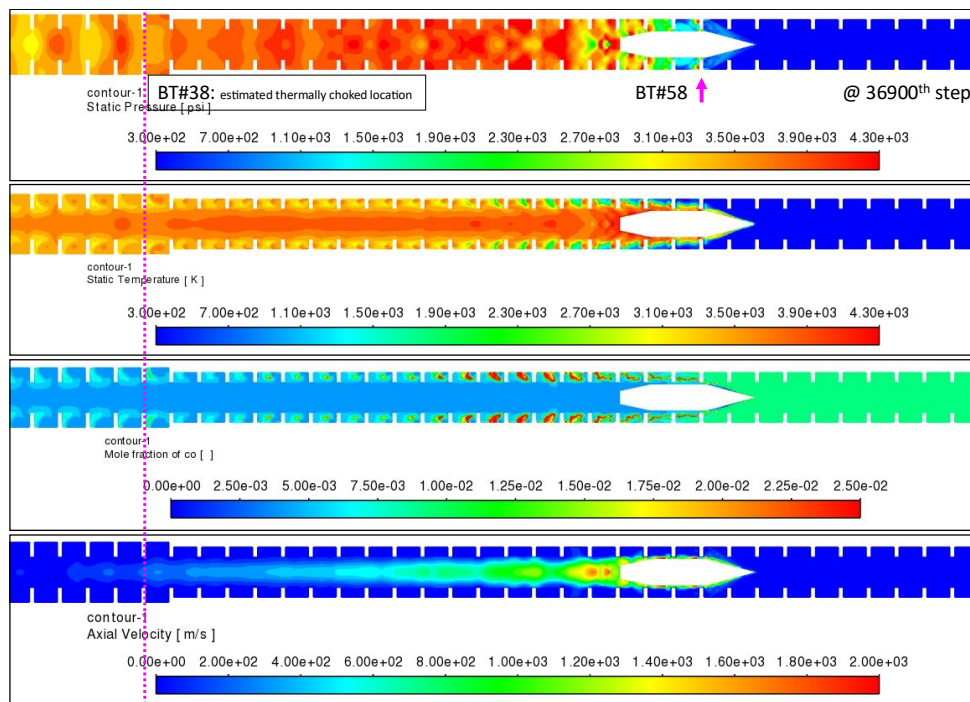


Figure 146 static-pressure, static-temperature, CO-mole fraction, and axial velocity maps of P380-2B-12-15 inside BTRA111-to-501 at 1.0 km/s near BT#58 at approximately 36900th time step (5e-8 s per time step)

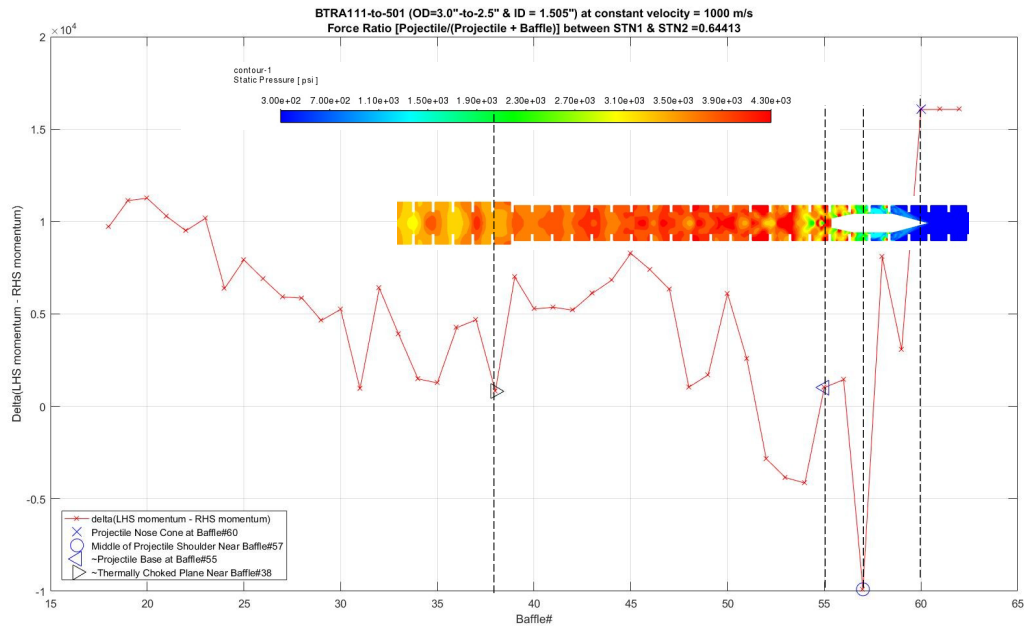


Figure 147 thermally choked location of P380-2B inside BTRA111-to-501 at 1.0 km/s and static pressure field

Figures below are associated with BTRA501 at 1.2 km/s case.

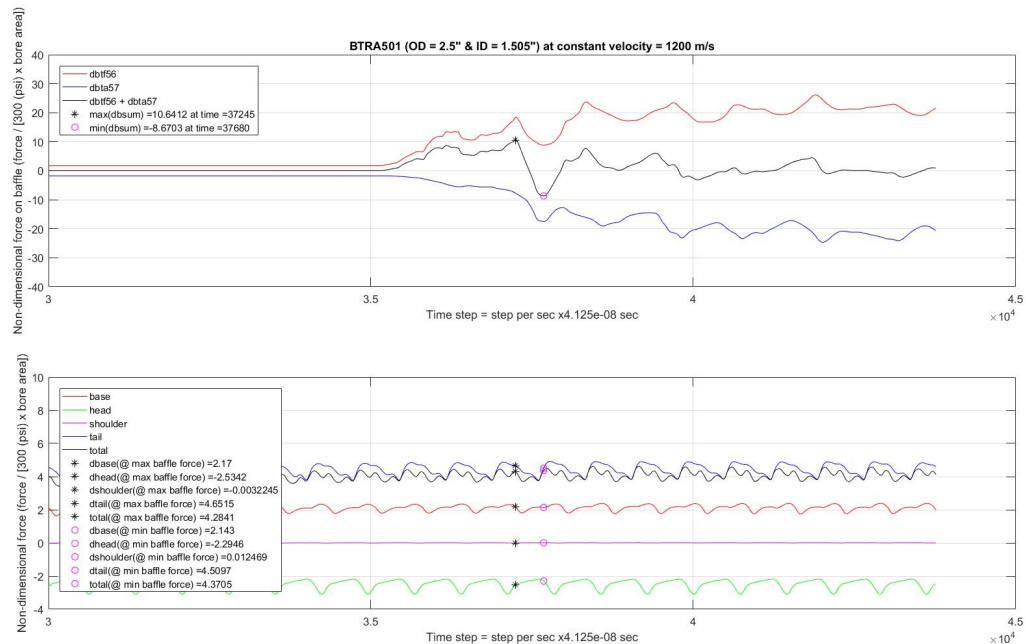


Figure 148 non-dimensional force signal on Baffle#56 in BTRA501 and non-dimensional thrust breakdown on P380-2B-12-15 at 1.2 km/s

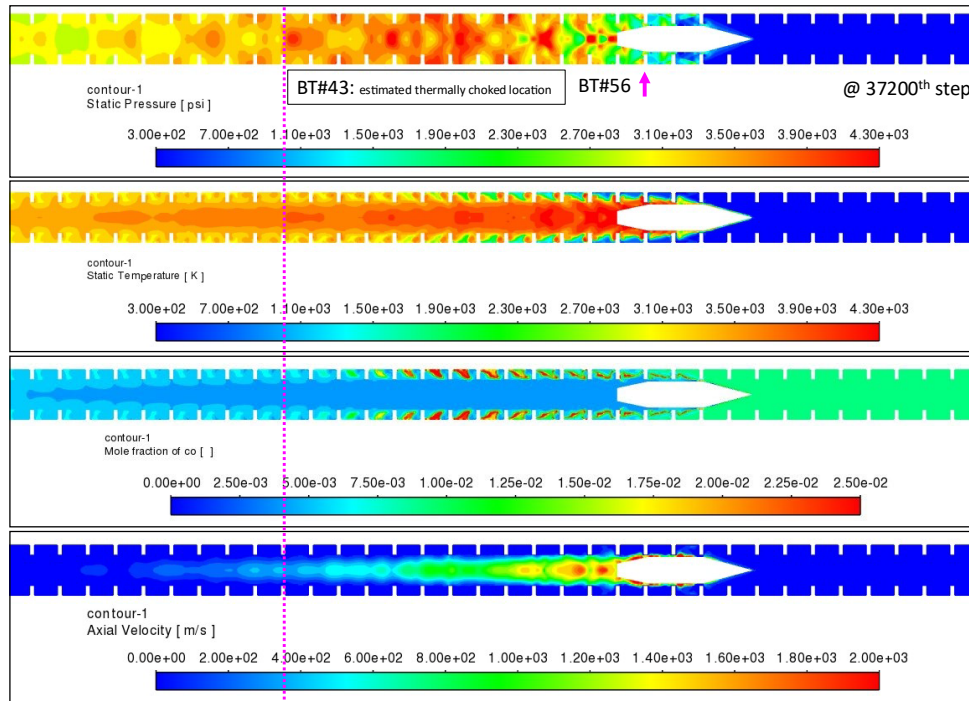


Figure 149 static-pressure, static-temperature, CO-mole fraction, and axial velocity maps of P380-2B-12-15 inside BTRA501 at 1.2 km/s near BT#56 at approximately 37200th time step (4.125e-8 s per time step)

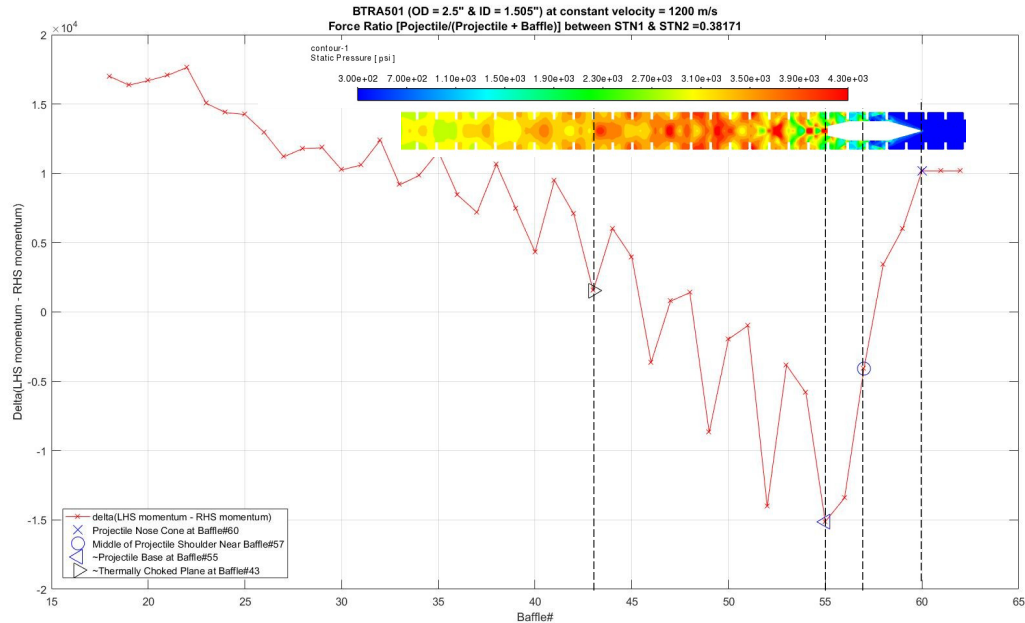


Figure 150 thermally choked location of P380-2B inside BTRA501 at 1.2 km/s and static pressure field

Figures below are associated with BTRA501 at 1.4 km/s case.

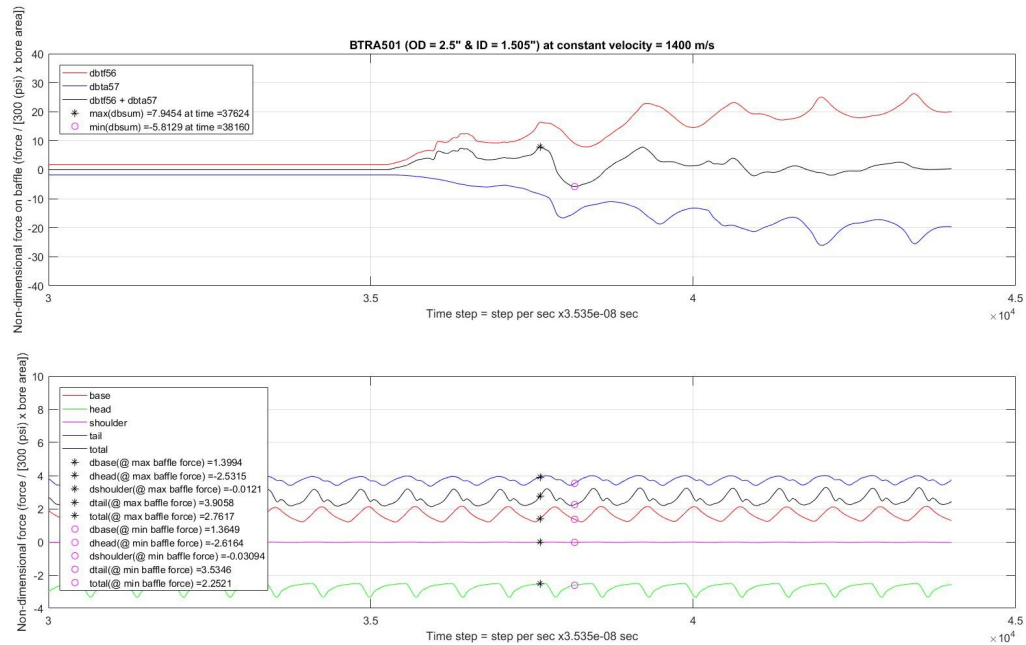


Figure 151 non-dimensional force signal on Baffle#56 in BTRA501 and non-dimensional thrust breakdown on P380-2B-12-15 at 1.4 km/s

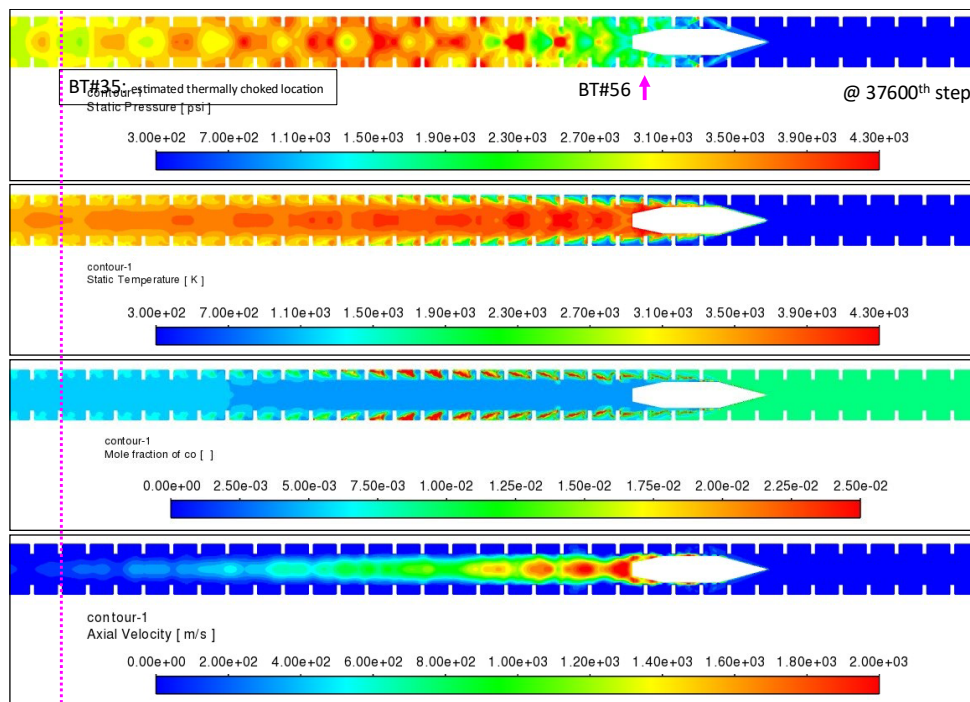


Figure 152 static-pressure, static-temperature, CO-mole fraction, and axial velocity maps of P380-2B-12-15 inside BTRA501 at 1.4 km/s near BT#56 at approximately 37600th time step (3.535e-8 s per time step)

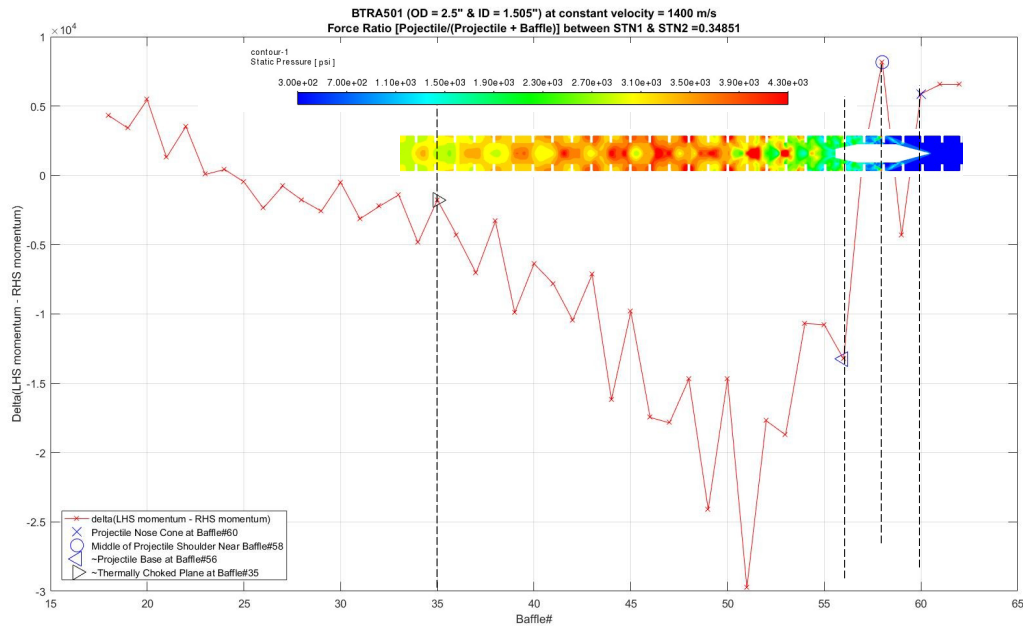


Figure 153 thermally choked location of P380-2B inside BTRA501 at 1.4 km/s and static pressure field

4. Recommendation for Future Works

There are many lessons learned and recommendations that are identified during CFD modeling of RTRA and BTRA research project that are summarized in this section. Some recommendations are based on CFD best practices that are not related to computational resources and provide a guidance for data post-processing and others might be applicable if additional computational resources are available to improve numerical accuracy.

4.1 Efficient Design of CFD Domain

An efficient CFD domain is designing a configuration that is capable of being updated in a relatively easy manner and it does not require a long time by an end-user to be modified. It is important to identify what key parameters are and what features might be subject to optimization

during the research project, e.g., number of baffles, baffle heights, baffle spacing, chamber fillet radii, normal baffles, slanted baffles, features related the projectile, etc. Just a few inputs should be required to update the CFD domain using a relational design philosophy to generate different features and zones. This practice allows a consistent design between cases and alleviates data extraction and CFD post-processing tasks. In general, a well-designed CFD domain improves gridding and mesh generation process.

4.2 Efficient Grid/Mesh Domains and Sufficient Grid Resolution to Resolve the Flow Field

The grid count and computational resources could limit what can be studied using CFD application, but an efficient cell zone and a proper grid strategy can drastically change the quality of data and flow field phenomena. Proper connection between different zones, identifying minimum cell size, maximum global cell size, growth rate, zone shapes, cell type, properly naming interfaces and boundaries, etc., can provide a great advantage to the researcher to control cell quality and cell counts in any desired location. Preparing CFD mesh/grid domain as described above might be a bit time consuming, e.g., naming each interface and zone with a proper and logical name, but this allows the researcher to be in a full control of mesh generation process. Also, a few iterations might be required to optimize zones and mesh grid quality. A proper mesh domain with fully named zones and interfaces help the solver to consume mesh information and initially guess the proper boundary conditions. A well-defined CFD mesh domain improves the performance of the solver and minimize the risk of unexpected solution divergence.

4.3 Solver Setup and Objectives

Setting up the solver to meet CFD study objectives and align it with the computational resources might be challenging and could require a few iterations to meet all requirements. The researcher must have a vision how the data will be used during the post-processing step. This allows collecting most, if not all, variables of interest at once in an efficient manner. There are embedded functions and capability within any solver that provide a great advantage to the user if these variables are set up a priori. For example, during BTRA study, more than 1035 specific flow field variables were recorded in the ASCII text file during simulations. Setting up the solver to collect data needed for post-processing step can be time consuming, but some steps could be scripted within Fluent [42] to reduce setup time.

Before collecting a full set of desired datasets, it is worth collecting a few sample cases to examine how different options within a solver can impact the accuracy of the results and time required for sub-iterations and solution convergence, i.e., monitoring species, mass, momentum, energy, and turbulence residuals. These observations and understanding of the computational resource limitation determine how to pick an appropriate solver with a reasonable accuracy to meet research objectives, but it may require a few iterations.

4.4 Efficient and Consistent Data Post-Processing Objectives

A CFD researcher should assume multiple datasets must be consumed and compared against each other and/or to experimental results. This vision allows the searcher to construct a platform to use CFD data as input and generate relevant plots and images for comparison. It is recommended to design the post-processing step such that it is relatively repeatable for each

case to generate consistent results. The post-processing application in this research project is done with MATLAB [59] and relevant functions to read ASCII files and store datasets in matrices and generate plots. The embedded post-processing tool within Fluent [42] solver is used to generate flow fields at desired locations in the laboratory frame of reference. Setting up a fixed and consistent dynamic range for any flow field quantity allows comparing different cases efficiently.

4.5 Considerations for Geometry Improvement if Computational Resources Available

The flow physics around the projectile, RTRA, and BTRA configurations are complex. If additional computational resources are available, it is recommended future cases be modeled in full 3-dimensional cases. The alternative option is to use $1/n^{\text{th}}$ of symmetry models such as $1/3^{\text{rd}}$ and/or $1/8^{\text{th}}$ models to study more complex phenomena. These options provide opportunities to model details like rails and/or better representation of RTRA and BTRA configurations. Features such as corner fillet radii inside a chamber and along the rail and/or features like discrete azimuthal holes pattern along some BTRA baffle walls can be modeled in 3-dimensional cases. It is speculated that adding some azimuthal holes on BTRA baffle wall may improve flow communication along adjacent chambers that may lead to a better turbulent mixing and a more efficient combustion and heat release. Also, asymmetrical feature on the projectile, e.g., patterns on the shoulder and the tail, can be implemented if 3-dimensional modeling is used.

4.6 Considerations for CFD Solver Improvement if Computational Resources Available

Improving combustion model in RTRA and BTRA should be a high priority if additional computational resources are available. The author proposes the following steps in subsequent order;

1. Refine mesh resolution by a factor of 2.0 and maintain the current BTRA combustion setup and compare results with datasets in this research project. Refine mesh resolution until grid convergence is fully confirmed.
2. Refine mesh resolution by a factor of 2.0 and reduce physical time step, but maintain the rest of the current BTRA combustion setup and compare results with datasets in this research project.
3. Compare results from Step#1 and Step#2 and determine an efficient grid resolution and an appropriate time step to improve numerical simulation by confirming stable convergence and residual drop at each physical time step.
4. Change the hybrid finite rate (Arrhenius rate) and Eddy Dissipation combustion model to Eddy Dissipation Concept (EDC) [55], but maintain the rest of the current BTRA combustion setup and compare results with datasets in this research project. It is recommended that grid quality and its resolution is adequate for Large Eddy Simulation (LES) calculation if EDC combustion model is used.
5. Increase number of reaction mechanisms while using EDC combustion model, but maintain the rest of the current BTRA combustion setup and compare results with datasets in this research project. Adding more reaction mechanism can drastically increase the computational cost in terms of data generation and data storage. Reaction

mechanism explored in Section 3.2 (3.2 CFD Modeling of BTRA Using Methane-Air Multi Reactions Mechanism Chemistry) are worth revisiting when EDC combustion model is implemented.

In addition to combustion modeling improvement, increasing virtual cross sections along RTRA and BTRA configurations to collect area averaged flow field quantities, adding certain measurement prods inside baffle chamber and/or baffle walls can improve accuracy and provide additional datasets during the post-processing step. Note that the size of each of ASCII file generated in this research study is under 1.0 gigabyte (GB) for each case. So, data handing, i.e., read and/or write data in real time, during data collection and post-processing should be tailored such that the short-term memory of computers (RAM) is not full to minimize computational time. Frequency of saving subset and/or full CFD datasets is important and must be optimized to assure high performance computers can collect data and minimize data loss and/or data corruption due to software and/or hardware failure.

5. Conclusions

Some characteristics of RTRA and BTRA operation have been identified through numerical simulations that some lead to increased combustion stability using axisymmetric projectiles. Also, there was need to acquire some numerical datasets in the RTRA and BTRA configurations to compare with experimental results. In addition, a more thorough exploration of geometrical features of the BTRA using CFD methods can guide design of future BTRAs. There was an interest to investigate the transition from one BTRA configuration to another BTRA configuration using CFD. These were the motivations to study RTRA and BTRA in reactive flow using CFD application.

Throughout this research study, a method of quantifying the rail and baffle drag was identified. The current RTRA and BTRA setup is capable of keeping track of forces exerted by the flow on all surfaces, i.e., on the projectile body and all baffled tube and rails walls, during the CFD simulation. Also, area-weighted average of various flow field quantities can be calculated at any desired axial location ahead and behind the projectile. Such capability allows the researcher to investigate the location of the theoretical thermally choked plane relative to the projectile and provide a methodology to estimate thrust ratio efficiency of RTRA and BTRA configurations.

5.1 RTRA with Axisymmetric Projectile Operation Summary

Here is a high-level summary of findings on RTRA research work;

1. Experiments conducted in RTRA operating with an axisymmetric projectile over the velocity range of 1000-1380 m/s in methane-air propellant at fill pressures from 21-28 atm (~300-400 psig). Non-dimensional thrust values from experiments (1.8 to 2.4 unit) were ~45% lower than the corresponding theoretical values for TCRA propulsive mode. However, they had the same decreasing trend with increasing Mach number.
2. CFD at 1.2 km/s did not show quasi-steady thrust behavior and it was unstarted.
3. CFD at 1.4 km/s reached a quasi-steady thrust during a long period of time (~5 ms) with a non-dimensional thrust value of ~4 unit, but it still showed an unstart behavior.
4. CFD at 14500 m/s² (from 1.4-1.5 km/s) was able to stabilize the flow field in a shorter amount of time than the transient period of the constant velocity simulation. The combustion wave front moved slowly forward into the projectile shoulder region as velocity increased. The rail influence dampened the shockwave reflections near the rail

when compared with those in the center of the channel. The experiments and simulations showed a strong shockwave at the end of the shoulder that corresponded to the combustion wave front. The sonic Mach number in the simulations was a 3-D surface stretching rearward behind the projectile

5. CFDs at 1.4 km/s showed serrations over the shoulder, tail and base impacted the combustion process. Serrations on the tail and recessed serration features on the base promoted vigorous combustion that led to unstart. Extending the shoulder length with a recessed serration over the tail suppressed the forward moving combustion process and stabilized the flow field. Extending the shoulder length without adding the recessed serration promoted the forward motion of the combustion wave front that resulted in an early unstart.

5.2 BTRA with Axisymmetric Projectile Operation Summary

Here is a high-level summary of findings on BTRA research work;

1. Experiments conducted in BTRA operating with an axisymmetric projectile over the velocity range of 750-1350 m/s in methane-air propellant at fill pressures at 25.5-30.6 atm (375-450 psig). Non-dimensional thrust values from experiments varied from 6.1 to 6.6 unit in one experiment while it decreased from 5.6 to 4.9 unit in the other experiment, while both experiments were ~45% lower than the corresponding theoretical values for TCRA propulsive mode.
2. The non-dimensional thrust of the short shoulder projectile at 1.0 km/s inside BTRA111 (3.0" outer-diameter) was about 3.4 unit. Whereas, it was about 6.7 unite inside BTRA501

(2.5" outer-diameter) and roughly reached a quasi-periodic state. The projectile had a non-dimensional thrust of 6.0-unit toward the end of simulation inside BTRA111-to-501 configuration while momentarily reached 6.7-unit before it was reduced. Reducing outer diameter to 2.2" and 2.0" led to early projectile unstart. These results suggest that reducing the height of baffle chamber can increase the non-dimensional thrust, but also could lead to unstart if is reduced beyond certain height.

3. The non-dimensional thrust of the short shoulder projectile inside BTRA501 configuration at 1.0, 1.1, 1.2, and 1.4 km/s was about 6.8, 5.0, 4.0, and 2.8 units accordingly and the projectile remain started.
4. The long shoulder projectile inside BTRA501 unstarted at 1.0 km/s. But it remains started at 1.2 km/s with non-dimensional thrust of roughly 5.0 unit that was about 1.0 unit larger than that of the short shoulder projectile at 1.2 km/s. This result suggests a longer shoulder projectile can provides a higher non-dimensional thrust if it remains started.
5. The short shoulder projectile was accelerated by a constant $8000g \text{ m/s}^2$ from 1.0 to 1.1 km/s inside BTRA501. It remains started and reached 5.8-unit non-dimensional thrust but did not reach a quasi-periodic solution. Whereas, when it was accelerated by a constant $19656g \text{ m/s}^2$ from 1.0 to 1.2 km/s, it reached a non-dimensional thrust of 4.0-unit toward the end of simulation
6. The long shoulder projectile was accelerated by a constant $19656g \text{ m/s}^2$ from 1.0 to 1.2 km/s inside BTRA501. It remains started and reached 3.8-unit non-dimensional thrust and roughly reached a quasi-periodic solution toward the end of the simulation.

7. When short shoulder projectile accelerated at $8000g$ m/s^2 from 1.0 to 1.1 km/s inside BTRA501 or accelerated at $19656g$ m/s^2 from 1.0 to 1.2 km/s, the projectile non-dimensional thrust roughly matched the constant velocity cases at 1.1 and 1.2 km/s accordingly. Whereas, the long shoulder projectile non-dimensional thrust at $19656g$ m/s^2 from 1.0 to 1.2 km/s was smaller than that of the 1.2 km/s constant velocity case (3.8 vs. 5.0-units).
8. A method was developed to estimate the location of theoretical thermally choked section behind the projectile base at constant velocity cases. This technique is used to quantify the overall projectile thrust and baffle drag between Station#1, i.e., a few baffle ahead of the projectile nose cone, and Station#2, i.e., a few baffles behind the projectile base that balances the momentum equation where the flow is thermally choked. This method is a first order approximation to locate the thermally choked location in laboratory frame of reference with the assumption that BTRA operations are thermally choked. Additional work may be needed to validate this assumption and further refine the ram accelerator theory and minimize differences between the theoretical model, experiments, and CFD simulations results.

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