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RAM ACCELERATOR THRUST MODELING FOR DIFFERENT BORES

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ABSTRACT

Ram accelerator (RAMAC) experiments have been carried out at laboratories around the world in various size bore facilities at fill pressures ranging from 1 to 20 MPa. The thermally choked ram accelerator propulsive mode has been the most extensively studied and is the focus of the modeling discussed here. The experiments utilized similar projectile geometries, propellants (CH_4, O_2, N_2), and fill pressures. Based on the unsteady, one-dimensional (1-D) conservation equations, thrust calculations using real-gas equations of state accounted for the compressibility effects of the combustion products and the influence of projectile acceleration. A virial type, namely the Boltzmann EoS, has been extensively used and its applicability to the RAMAC calculations for a 38-mm-bore has been widely demonstrated. An empirical EoS, such as that of Becker, Kistiakowsky and Wilson (BKW), is examined in this pressure range for different bore dimensions. The objective of this work is to improve the unsteady 1-D model in order to better predict the thrust-Mach behavior of the thermally choked ram accelerator propulsive mode. Velocity-distance calculations are in good agreement with experimental data from 25-mm, 30-mm, 38-mm, 90-mm, and 120-mm-bore experiments.

KEYWORDS: ram accelerator, thrust, equation of state, unsteady flow

1. INTRODUCTION

The ram accelerator [1], or RAMAC, accelerates projectiles with a propulsive cycle based on an in-tube ramjet engine cycle. RAMAC systems have successfully accelerated projectiles up to velocities of nearly 3 km/s in tubes filled with gaseous propellant, namely, $CH_4/O_2/N_2$. Experimental investigations on the RAMAC concept have been carried out at; University of Washington (UW) 38-mm-bore facility at propellant fill pressures up to 20 MPa [2,3,4]; French-German Research Institute Saint Louis (ISL) 30-mm-bore and 90-mm-bore devices at fill pressures up to 4.5 MPa [5]; US Army Research Laboratory (ARL) 120-mm-bore device at fill pressures up to 8.5 MPa [6]; and Tohoku University (TU) 25-mm-bore device at fill pressures up to 3.5 MPa [7]. Corresponding computational fluid dynamic (CFD) studies have also been carried out at other institutions such as University of Poitiers, France [8,9,10], Seoul National University, Korea [11], National Research Laboratory, USA [12], and ARL [13].

Velocity regimes of ram accelerator operator are categorized by the ratio of projectile velocity (V) to the Chapman-Jouguet (CJ) detonation speed D_{CJ} of the propellant [3]. In the subdetonative velocity regime ($V < D_{CJ}$), RAMAC thrust-Mach number characteristics are readily modeled by assuming a subsonic combustion zone that is terminated by thermal choking behind the projectile, as shown in Fig. 1. In this propulsive mode, thrust generated by the high projectile base pressure results from a normal shock system stabilized on the projectile body by thermal choking of the flow at the full tube area [1,2]. Experiments show that this propulsive mode operates effectively in the Mach number range of M= 3 – 4.5.

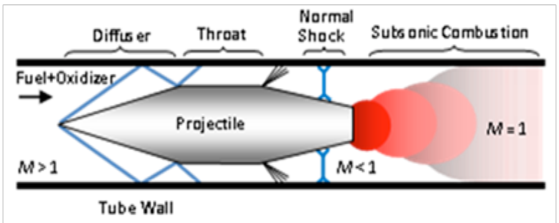

Figure 1: Flow field schematic of the thermally choked ram accelerator

A chemical equilibrium code (TARAM) has been used in prior studies for calculating the unsteady thrust of the thermally choked RAMAC propulsive mode. A good agreement between 1-D unsteady theory and 38-mm-bore RAMAC experiments was observed [14,15]. In order to better predict RAMAC thrust when the fill pressure is increased beyond 3 MPa [16] real-gas equations of state (EoS) (e.g.; Boltzmann, Redlich-Kwong, Percus-Yevick, Becker-Kistiakowsky-Wilson (BKW)) were included in the TARAM code.

The aim of the present paper is to show the efficacy of this unsteady, real-gas 1-D computational model using specific EoS, namely, Boltzmann and BKW EoS. It is based on the comparison of calculated velocity profile with experimental data from the 25-mm, 38-mm, 90-mm, and 120-mm-bore RAMAC facilities of TU, UW, ISL, and ARL, respectively. These experiments utilized similar projectile geometries, propellants (CH_4, O_2, N_2), fill pressures (3-5 MPa), and velocity range (1.1-1.8 km/s) as listed in Table 1 (Section 4). The projectile materials (Al, Mg, Ti), however, differed in these experiments. The theoretical development of the 1-D model used by the TARAM code is presented.

2. ONE DIMENSIONAL MODEL

The quasi-steady one-dimensional thrust-Mach number model for the thermally choked RAMAC propulsive mode applies the 1-D conservation equations in the projectile reference frame (see Fig. 2). This model assumes steady flow enters the control volume at supersonic velocity (denoted as state 1) and exits at sonic velocity (denoted as state 2), where it has attained chemical equilibrium while conserving mass and energy. The sum of the streamwise momentum and pressure forces between the incoming and the outgoing flows is the net axial force (thrust) applied to the projectile. The thrust-Mach number characteristics calculated in this manner compare very well with experiments when the rate of acceleration and the fill pressure are below 100 km/s^2 and 2 MPa, respectively [1,2].

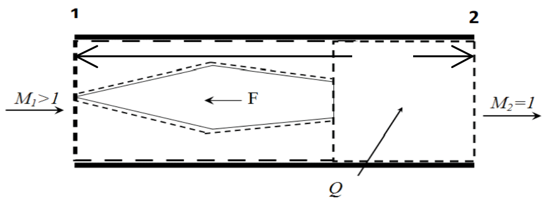

Figure 2 : Control volume for 1-D model of the thermally choked RAMAC

When the fill pressures were greater than 2.5 MPa, the inclusion of real-gas EoS in the quasi-steady thrust model for the thermal choked propulsive mode resulted in better agreement between the predicted velocity-distance profiles and experimental results [17,18]. For very high projectile acceleration (>100 km/s^2), a revised unsteady model that includes the effects of a real-gas EoS for the combustion products was developed [4,19]. This model accounts for the effect of rapid projectile velocity change on the net thrust by incorporating variations in combustion zone length, L_{CV}, and mass of propellant within the control volume. The influence of combustion heat release on the rate of change of axial streamwise thrust is determined by the introduction of a non-dimensional chemical heat release parameter, $Q = \Delta q/c_{p1}T_1$ and a non-dimensional thrust parameter, F/p_1A_1, acting on the control volume (CV), where A, c_p and p denote respectively the cross sectional area of the tube, heat capacity and static pressure. The thrust predicted by this RAMAC model is F.

Analysis of the conservative equations yields a readily applicable set of equations in the form expressed by Bundy *et al.* [4] and Bauer *et al.* [19]. After some algebraic manipulation of these relationships, while specifying the end state to be thermally choked; i.e., $M_2^2 = \Gamma_2 R_2 T_2 = 1$, where Γ is the adiabatic heat capacity rate. Introducing a real-gas EoS, namely, $pv/RT = \sigma(v,T)$, where v, T and R in the compressibility factor σ are respectively the specific volume, temperature and gas constant, the following expressions are derived:

$$\frac{T_2}{T_1} = \frac{c_{p1}}{c_{p2}} \frac{\left(\eta_1 + \frac{\gamma_1 R_1 M_1^2}{2c_{p1}} + Q\right) - \frac{7\alpha}{2c_{p1}T_1}}{\left(\eta_2 + \frac{\Gamma_2 R_2}{2c_{p2}}\right)\left(1 - \frac{\alpha}{\gamma_1 R_1 M_1^2 T_1}\right)} \quad (1)$$

$$\frac{p_2}{p_1} = \frac{\sigma_2}{\sigma_1}\left(M_1\sqrt{\frac{\gamma_1 R_2}{\Gamma_2 R_1}} - \frac{\alpha}{R_1 M_1 T_1}\sqrt{\frac{R_2}{R_1\gamma_1\Gamma_2}}\right)\sqrt{\frac{T_2}{T_1}} \quad (2)$$

$$\frac{F}{p_1 A_1} = \frac{\alpha}{R_1 T_1} + \frac{p_2}{p_1}\left(1 + \frac{\Gamma_2}{\sigma_2}\right) - \left(1 + M_1^2\frac{\gamma_1}{\sigma_1}\right) \quad (3)$$

with:

$$\alpha = L_{CV} a_p \quad ; \quad \Gamma = \left.\frac{\partial h}{\partial e}\right)_s \quad (4)$$

a_p denotes the acceleration of the projectile, e, h and s being the specific internal energy and enthalpy and entropy, respectively.

Unlike in the quasi-steady-state formulation of the thermally choked RAMAC thrust [1,2], the preceding equations show that the non-dimensional thrust, F/p_1A_1, is a direct function of both the length of the control volume, L_{CV}, and the projectile acceleration, a_p. An iterative procedure was used to solve for the value of α in Eq. (3), which is an acceleration parameter relating the combustion zone length and projectile acceleration as a function of Mach number for an arbitrarily chosen value for L_{CV} [19]. Based on experimental observations of the luminosity of the flow in 38-mm-bore experiments [2], a value of $L_{CV} = 2L_P$, where L_p is the projectile length, was initially chosen (i.e. 306 mm in this instance). It was later found that the unsteady thrust predictions were highly dependent on the assumption of L_{CV} dimensions [19]; thus more accurate combustion zone length estimates were needed.

Previous CFD studies, utilizing both axisymmetric and 3-D simulations, addressed laminar and turbulent flows [8,9]. These CFD simulations provided detailed flow field information arising from projectile-tube interactions and their influence on the thrust. The calculated peak amplitudes of pressure and temperature and the location of the shock-wave system were validated against available test data [9]. The length of the combustion zone was determined from the projectile base to the point where the area-averaged axial Mach number equals unity [14,15].

3. AVAILABLE EQUATIONS OF STATE FOR COMBUSTION PRODUCTS

RAMAC operation at fill pressures in the range of 7 MPa to 30 MPa are of interest for launching massive payloads (>1000 kg) at modest accelerations (<50 km/s^2) [20,21] and achieving very high accelerations comparable with military weapons (>200 km/s^2). Thus it is of interest to develop the ability to incorporate equations of state (EoS) that are appropriate for the RAMAC operation at these elevated fill pressures. Numerous EoS based on generalized empirical and theoretical considerations have been developed by Heuzé [22]. Only the general forms of each EoS incorporated in the TARAM computer program that were used in the present study are presented here.

Several EoS are suited to predict the thermo-chemical properties of combustion products at pressures corresponding to the end state of the RAMAC, which can range from 50 MPa to 1000 MPa. A virial type, namely the Boltzmann EoS, has been extensively used and its applicability to the RAMAC calculations for a 38-mm-bore has been widely demonstrated [4,17,23]. Nevertheless, the use of another EoS that is appropriate for the pressure range under consideration here, such as the Becker, Kistiakowsky and Wilson (BKW) EoS, is worth investigating for different bore dimensions. The main reason is its applicability to a wide range of temperatures and pressures of combustion products that cover the whole field of gaseous to condensed explosives, based on the appropriate choice of its adjustable parameters.

3.1 Boltzmann

The Boltzmann EoS [24] adequately predicts the Chapman-Jouguet properties when the pressure of combustion products does not exceed 200 MPa [25]. This equation of state treats the individual molecules as hard spheres and the mixing rule accounts only for interactions of similar species. The Boltzmann expansion for the compressibility factor is computed by the formula below:

$$\sigma = 1 + x + 0.625x^2 + 0.287x^3 + 0.193x^4 \tag{4}$$

where x is defined as:

$$x = \sum_i \frac{X_i B_i}{v_i} \tag{5}$$

B_i represents the covolume of species I which are in a molar fraction X_i

3.2 Becker-Kistiakowsky-Wilson (BKW)

This EoS was introduced in 1921 by Becker, and later modified by Kistiakowsky and Wilson [26]. It can be presented as follows:

$$\frac{pv}{RT} = 1 + xe^{\beta x} \tag{6}$$

with:

$$x = \frac{\kappa B}{V(T+\theta)^{\alpha}} \tag{7}$$

with:
$$B = \sum_i x_i b_i \tag{8}$$

where α, β, χ, θ are semi-empirical constants that must be adjusted. In particular, b_i are the specific co-volumes defined for this EoS. This formulation of the BKW EoS is mostly used for condensed explosives; however, previous research by Heuzé [22] and Bengherbia *et al.* [14] showed that it could be applied to the calculation of gaseous detonation characteristics at extremely elevated pressures, if all the adjustable parameters were appropriately set.

4. RESULTS AND DISCUSSION

The one-dimensional TARAM code for unsteady RAMAC thrust calculations was applied here using the ideal gas, Boltzmann, and BKW EoS respectively, whose adjustable parameter values were validated by comparison with experimental CJ speeds [27,28]. The TARAM code calculates real-gas effects for each EoS by changing how the parameter σ is computed for both the combustion products and reactants. In order to investigate the applicability of these EoS for predicting the thrust of the RAMAC thermally choked propulsive mode, the present study is aimed at comparing the calculated velocity profiles with experimental results from facilities having bore dimensions ranging from 25 mm to 120 mm, as shown in Table 1. All experimental parameters needed to predict the velocity profiles of the experiments are provided with the assumption that the reactant temperatures were all 300 K and the combustion zone length was 350 mm regardless of bore dimension. Details of the facilities and the results of these particular experiments can be found in cited references [5,7,13,29].

Facility	Bore (mm)	Propellant (moles)	Pressure (MPa)	Velocity Range (km/s)	Projectile Mass (kg)	L_p (mm)	L_{CV} (mm)
TU	25	$2.8CH_4+2O_2+5.7N_2$	3.5	1.23 – 1.92	0.022	101	451
UW	38	$3.0CH_4+2O_2+5.7N_2$	5.1	1.15 – 1.86	0.109	153	503
ISL	90	$3.0CH_4+2O_2+9.9N_2$	4.0	1.33 – 1.67	1.332	396	746
ARL	120	$3.0CH_4+2O_2+10N_2$	5.2	1.25 – 1.46	4.332	522	872

Table 1: Experimental test data matrix from different RAMAC facilities.

Experimental velocity-distance data from these four facilities are plotted in Fig. 3 along with the corresponding 1-D modeling results using the Boltzmann and the BKW EoS with the L_{CV} for each data set listed in Table 1. The theoretical velocity-distance plots are adjusted to intersect the first data point from each experiment to properly represent the performance expectations of the thermally choked RAMAC propulsive mode. The deviation between Boltzmann and BKW EoS velocity-distance calculations is most pronounced in the higher fill pressure cases of the UW and ARL data, which is consistent with the observation that BKW EoS predictions for D_{CJ} increase with increasing fill pressure at a greater rate than D_{CJ} predictions based on Boltzmann EoS.

It is evident that the Boltzmann predictions agree with experiments better than BKW for the data from UW and ARL plotted here, and the BKW EoS is in better agreement for the TU and ISL data. Since the BKW calculations seem to favor lower fill pressure conditions at two very different projectile size scales (25 mm and 90 mm RAMACs), this implies that it is the better choice for EoS at fill pressures below 4 MPa. Conversely, the Boltzmann EoS predictions are in very good agreement with the experiments at fill pressures greater than 5 MPa, regardless of bore dimension and projectile length.

Note that the experimental velocity data begin to deviate upward from the theoretical predictions in all cases. This behavior is attributed to the combustion process moving up on the projectile body and the cessation of thermal choking at full tube area behind the projectile

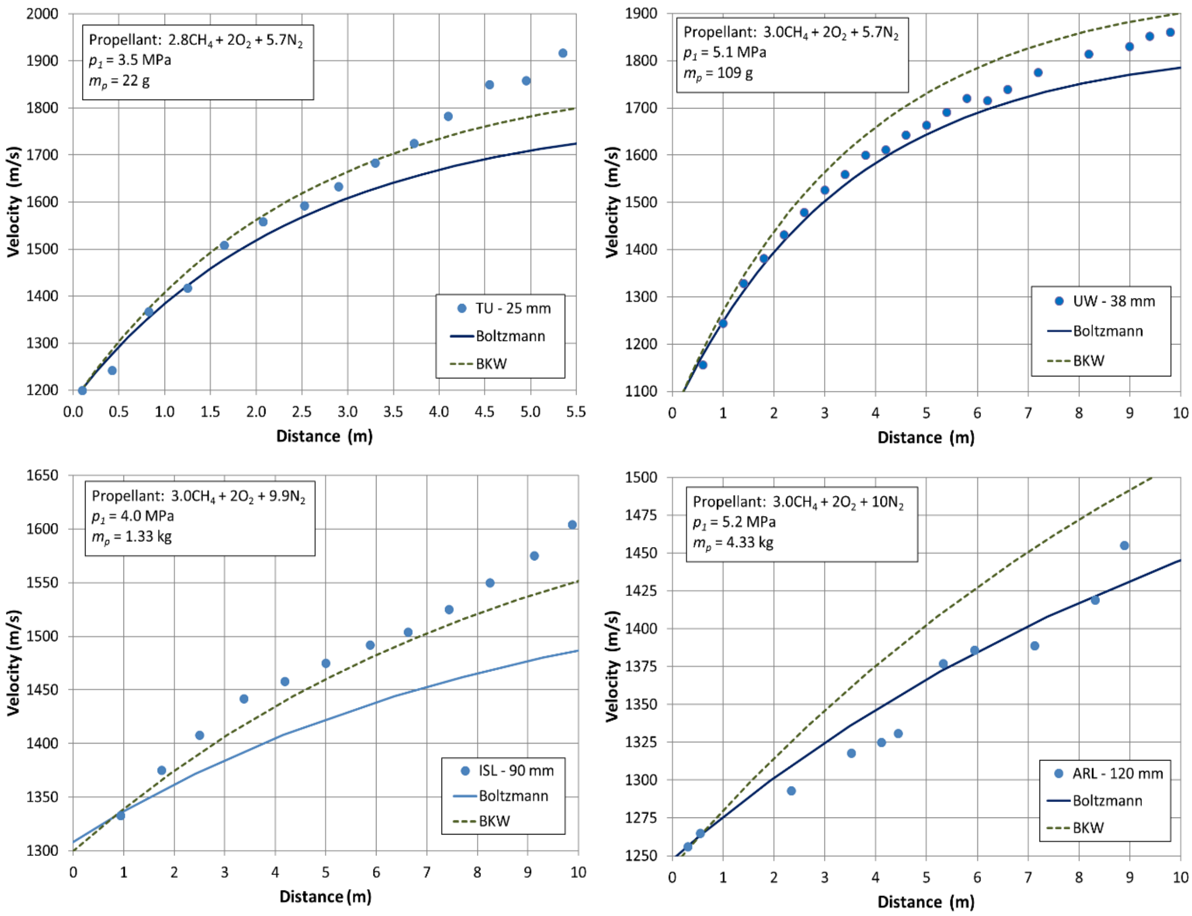

Figure 3: Experimental velocity-distance data compared with unsteady, 1-D theory using a constant length combustion zone (350 mm) and the Boltzmann and BKW EoS (experimental

as the projectile velocity approaches D_{CJ}. An investigation of the factors leading to these thrust deviations from theory are beyond the scope of present work, thus experimental data at even higher velocities from these experiments than those shown are not plotted nor considered.

CONCLUSION

Real-gas and unsteady effects were included in the thermally choked ram accelerator propulsive mode model to enhance accuracy of the predicted thrust vs. Mach number characteristics. The applicability of this propulsive model was tested by applying it to experiments from facilities having bores ranging from 25 to 120 mm. Comparisons of the computed velocity profiles with experiments show that, among the equations of state considered, the Boltzmann EoS, despite its simple molecular interaction law, is appropriate for 5 MPa propellant fill pressure in the 38-mm and 120-mm-bore facilities. Although it tends to over-predict the experimental data from the 38-mm-bore device, the empirical BKW EoS turns out to improve the theoretical agreement with experimental data from the 25-mm and 90-mm-bore facilities where the fill pressures were less than 4 MPa. Calculations which include unsteady effects are generally in better agreement with experiments than those using a quasi-steady model, even when using a fixed-length for the combustion zone.

REFERENCES

[1] A. Hertzberg, A.P. Bruckner, D.W. Bogdanoff. Ram Accelerator: A New Chemical Method for Accelerating Projectiles to Ultrahigh Velocities. *AIAA J.*, **Vol. 26**, pp. 195-203 (1988).

[2] A.P. Bruckner, C. Knowlen, A. Hertzberg, D.W. Bogdanoff. Operational Characteristics of the Thermally Choked Ram Accelerator. *J. of Propulsion and Power*, **Vol. 7, No. 5**, pp. 828-836 (1991).

[3] A. Hertzberg, A.P. Bruckner, C. Knowlen. Experimental Investigation of Ram Accelerator Propulsion Modes. *Shock Waves*, **Vol. 1, No. 1**, pp. 17-25 (1991).

[4] C. Bundy, C. Knowlen, A.P. Bruckner. Unsteady Effects on Ram Accelerator Operation at Elevated Fill Pressures. *J. of Propulsion and Power,* **Vol. 20**, pp. 801-810 (2004).

[5] M. Giraud, J.F. Legendre, M. Henner. *RAMAC in Subdetonative Propulsion Mode: State of the ISL Studies* in "Ram Accelerators". Takayama K., Sasoh A. (eds.), Springer-Verlag, Heidelberg, pp. 65-78 (1998).

[6] D.L. Kruczynski, F. Liberatore. Experimental Investigation of High Pressure/Performance Ram Accelerator Operation in "Proceedings of *AIAA Aerospace Sciences Meeting and Exhibit", 96-2676,* Reno, NV, USA (1996).

[7] Y. Hamate, A. Sasoh, K. Takayama. High Acceleration Using Open-Base Projectile. *J. of Propulsion and Power,* **Vol. 19, No. 2**, pp. 801-810 (2003).

[8] T. Bengherbia, Y. Yao, P. Bauer. Computational Investigation of Transitional Viscous Flow over a Ram Accelerator Projectile in Sub-Detonative Propulsion Mode in "Proceedings of *AIAA Aerospace Sciences Meeting and Exhibit", AIAA 2006-0558,* Orlando, FL, USA (2006).

[9] T. Bengherbia, Y. Yao, P. Bauer, C. Knowlen. Numerical Investigation of Thermally Choked Ram Accelerator in Sub-Detonative Regime Mode in "Proceedings of *AIAA Aerospace Sciences Meeting and Exhibit", AIAA 2009-0635,* Orlando, FL, USA *(*2009).

[10] T. Bengherbia, Y. Yao, P. Bauer, C. Knowlen. CFD-based 1D Modeling of the Thermally Choked Ram Accelerator in "Proceedings of *AIAA Aerospace Sciences Meeting and Exhibit", AIAA 2012-982,* Nashville, TN, , USA (2012).

[11] J.-Y. Choi, B.-J. Lee, I.-S Jeung. Computational modeling of high pressure combustion mechanism in scram accelerator. *J. Phys.* IV, **Vol. 10**, pp. 121-131 (2000).

[12] C. Li, K. Kailasanath. Initiation Mechanism of the Thermally Choked Combustion in Ram Accelerators. *J. of Propulsion and Power*, **Vol. 15, No. 1**, pp. 151-153 (1999).

[13] M.J. Nusca, D.L Kruczynski. Reacting Flow Simulation for Large-Scale RAMAC. *J. of Propulsion and Power*, **Vol. 12, No. 1**, pp. 61-69 (1996).

[14] T. Bengherbia, Y.F Yao, P. Bauer, C. Knowlen. One-dimensional Performance Modeling of the RAMAC in Subdetonative Regime. *Aerotecnica, J. of Aerospace Sci., Tech. and Syst.*, **Vol. 89**, pp. 3-13 (2010).

[15] T. Bengherbia, Y.F Yao, P. Bauer, M. Giraud, C. Knowlen. Improved 1-D Unsteady Modeling of the Thermally Choked RAMAC in the Sub-Detonative Propulsion Mode. *J. of Appl. Mech.*, **Vol. 78**, pp. 150-167 (2011).

[16] P. Bauer, T. Bengherbia, C. Knowlen, A.P. Bruckner, Y. Yao, M. Giraud. Equations of State Implementation for 1-D Modelling of Performance in Ram Accelerator Thermally Choked Propulsion Mode. *Int. J. Engineering Systems Modelling and Simulations*, **Vol. 7, No. 2**, pp 71-79 (2015).

[17] P. Bauer, C. Knowlen, A.P. Bruckner. Real gas effects on the prediction of ram accelerator performance. *Shock Waves,* **Vol. 8**, pp. 113-118 (1998).

[18] P. Bauer, C. Knowlen. Compressibility effects of unreacted propellant on thermally choked ram accelerator performance. *Eur. Phys. J. Appl. Phys.,* **Vol. 21**, pp.233-238 (2003).

[19] P. Bauer, C. Knowlen, A.P. Bruckner. Modeling Acceleration effects on Ram Accelerator Thrust at High Pressures. *J. of Propulsion and Power*, **Vol. 21**, pp. 955-957 (2005).

[20] K.W. Naumann, A.P. Bruckner. Ram Accelerator Ballistic Range Concept for Softly Accelerating Hypersonic Free-Flying Models. *J. of Aircraft*, **Vol. 31, No. 6**, pp 1310-1316 (1994).

[21] C. Knowlen, A.P. Bruckner. Direct Space Launch Using Ram Accelerator Technology in "Proceedings of *Space Technology and Applications International Forum-2001"*, ed M.S. El-Genk, American Institute of Physics, pp 583-588 (2001).

[22] O. Heuzé. Equations of State of Detonation Product. *Phys. Rev. A,* **Vol. 34**, pp. 428-432 (1986).

[23] D.L. Buckwalter, C. Knowlen, A.P. Bruckner. Real Gas Effects on Ram Accelerator Analysis in "Proceedings of *AIAA", AIAA 97-2894* (1997).

[24] P. Bauer, C. Brochet, S. Krishnan. Detonation Characteristics of Gaseous Ethylene, Oxygen and Nitrogen Mixtures at High Initial Pressures. *Progress in Aeronautics and Astronautics*, Ed. AIAA, New York, NY, **Vol. 75**, pp. 408-422 (1981).

[25] P. Bauer, H.N. Presles, O. Heuzé, C. Brochet. Equation of State for Dense Gases. *Archivum Combustionis*, **Vol. 5**, pp. 315-320 (1985).

[26] C. L. Mader. *Detonation Properties of Condensed Explosives Computed Using the Becker–Kistiakowsky–Wilson Equation of State* in Report-LA-2900, Los Alamos Scientific Laboratory, NM, USA (1963).

[27] P. Bauer, M. Dunand, H.N. Presle. Detonation Characteristics of Gaseous Methane-Oxygen-Nitrogen Mixtures at Extremely Elevated Initial Pressure. *AIAA Progress in Aeronautics and Astronautics*, **Vol. 133**, pp. 56-62 (1991).

[28] P. Bauer, J.F. Legendre, C. Knowlen, A.J. Higgins. Transition of Detonation on Insensitive Dense Gaseous Mixtures in Tubes in "Proceedings of *AIAA Aerospace Sciences Meeting and Exhibit", AIAA 96-2682,* Reno, NV, USA (1996).

[29] T. Bengherbia, Y.F. Yao, P. Bauer, C. Knowlen. Thrust Prediction in Thermally Choked Ram Accelerator in "Proceedings of *AIAA Aerospace Sciences Meeting and Exhibit", AIAA 2010-1129,* Orlando, Fl, USA (2010).