Defence Science Journal, Vol. 54, No. 3, July 2004, pp. 259-270

Computational Examination of Parameters Influencing Practicability of Ram Accelerator

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ABSTRACT

The problems concerning practicability aspects of a ram accelerator, such as intense in-bore projectile ablation, large accelerator tube length to achieve high projectile muzzle velocity, and high entry velocity of projectile in the accelerator tube for starting the accelerator have been examined. Computational models of the processes like phenomenon of projectile ablation, flow in the aero-window used as accelerator tube-end closure device in case of high drive gas filling pressure in the ram accelerator tube have been presented. New projectile design to minimise the starting velocity of the ram accelerator is discussed. Possibility of deployment of ram accelerator in the defence-oriented role has been investigated to utilise its high velocity potential.

Keywords: Ram accelerator, projectiles, propulsion, computational fluid dynamics, modelling, flow parameters, projectile velocity, flow regime, fuel-oxidiser mixture, hit probability, projectile ablation

NOMENCLATURE

t	Flow temperature
M	Flow Mach number
M ©	Projectile Mach number
A	Flow area
Cp	Specific heat
κ	Thermal conductivity
Le	Lewis number
Nu	Nusselt number
lc	Characteristic length
mc	Mass transfer coefficient
R	Gas constant
m	Mass of ablatant coated projectile
sa	Surface area
ξ	Density of ablatant vapour
a - *j*	Constant coefficients
a	Angle of nozzle axis with the horizontal
z	Distance of detonation wave end from the projectile front shoulder
Rf	Recovery factor
p	Flow pressure
p	Flow density
V	Projectile velocity
A®	Accelerator tube area
μ	Coefficient of viscosity
Y	Ratio of specific heats
Pr	Prandtl number

Revised 17 May 2004

Re	Reynolds number
hc	Average heat transfer coefficient
mt	Mass transfer rate
N	Velocity profile parameter
L	Accelerator tube length
P	Ablatant vapour pressure
F	Thrust at accelerator muzzle
υ	Prandtl Mayer angle
T	Time elapsed after projectile entry in the accelerator tube
ϕ	In-flight inclination of projectile with the horizontal
e	Efficiency factor

Subscripts

e	At entry point in the accelerator
abl	Ablatant vapour
a	At 11000 m altitude
1-5	Stations of an aero-window
m	At accelerator muzzle
mix	Fuel-oxidiser mixture
wall	Projectile wall

1. INTRODUCTION

Capability of propelling the projectile up to 10,000 m/s and more categorises ram accelerator into a futuristic device with immense potential in space applications, study of hypervelocity impacts, and other possible defence-oriented roles. Although experimentation on ram accelerator at a small scale and at conceptual level is reported to have met with success[1], its large-scale implementation and common use has been prevented by various technological drawbacks. Firstly, combustion of fuel-oxidiser mixture in a self-ignition, detonation-type ram accelerator generates extremely high temperature which causes intense projectile ablation. Secondly, large accelerator tube length is required to achieve high projectile muzzle velocity. Accelerator tube length can extend up to few thousand meters in the case of space applications which appears impractical. Thirdly, entry velocity of a projectile in the accelerator tube has to be very high to start or put the accelerator in the functional mode. For instance, projectile entry velocity above 3000 m/s is required for operation of self-ignition, detonation-type ram accelerator. Velocity of such a magnitude is impossible to be generated by the existing technologies.

The paper attempts to address all the aspects which influence practicability of a ram accelerator. This calls for a continuous time-dependent modelling of the entire flow regime during the travel of a projectile in the ram accelerator tube. Models based on computational fluid dynamics (CFD) are best suited for this purpose, but computations involved in this technique are enormous. Therefore, the treatment adopted in this paper has been simplified by framing comprehensible mathematical models with certain assumptions. These models are utilised to study the flow regime at various discrete projectile velocity and positions in the accelerator tube. As such, the numerical values of flow parameters presented in the paper are not claimed to be highly accurate. Nevertheless, these give a fair amount of idea about the order of their magnitude.

The analysis presented in this paper deals with an oblique, self-ignition, detonation-type ram accelerator operating on the fuel-oxidiser mixture of $2H_2 + O_2$. Output projectile velocity of 5000 m/s from the accelerator is considered in the analysis as it is considered optimum for utility of ram accelerator in the defence role. Ballistic computations of the projectile launched from the accelerator to defeat an enemy fighter aircraft are carried out to determine the fighting Mach number of the projectile and the time taken by it to reach the combat height.

Initially, a miniature solid projectile of 25.8 mm calibre and 147 mm length was used in the computation. This projectile configuration was deliberately selected since research work was being carried out elsewhere with this configuration[2], results of which have helped in validation of the approach adopted for analysis during the course of this study. Computations were later extended to a high calibre projectile which needs to be employed to accommodate the guidance package for enhancing its hit probability.

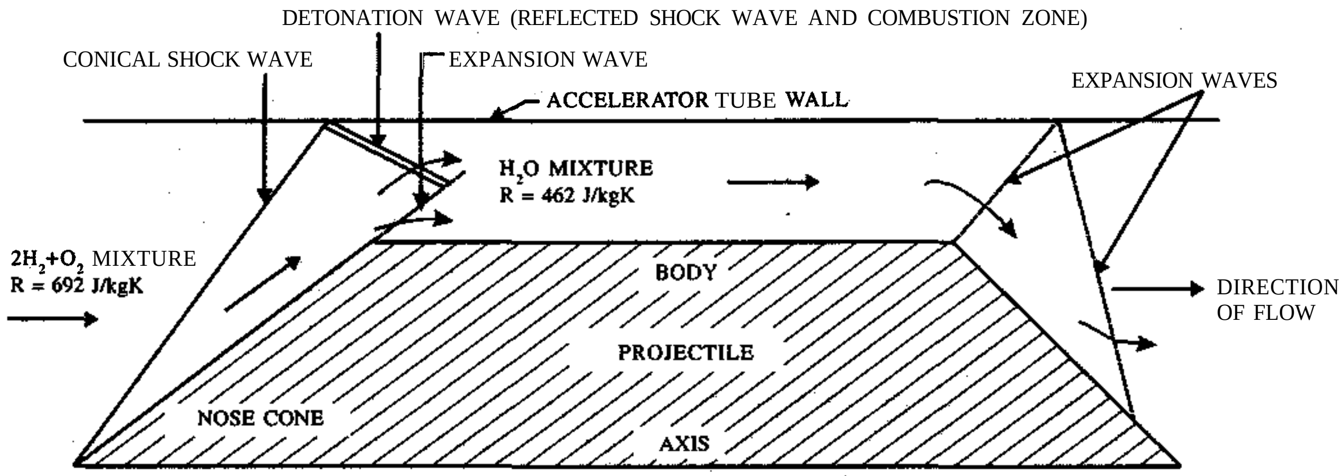

Figure 1. Schematic of flow processes in an oblique detonation ram accelerator

2. PROJECTILE ABLATION

Entry of a projectile with hypersonic Mach number in the ram accelerator tube initiates a conical shock wave at the tip of the projectile, resulting in compression of reactant flow gases ($2H_2+O_2$) in the region between the projectile nose cone and the tube wall (Fig. 1).

In the process, temperature of the projectile nose cone surface rises, leading to its severe mass transfer or ablation. Similarly, high temperature product gases (H_2O) formed by the combustion of reactant mixture ahead of the nose cone over the projectile body cause projectile body ablation. High temprature product gases include H_2O and other mass fraction species like OH, H, O, HO_2, H_2O_2, etc. with fixed mass fractions which can be determined from separate equilibrium combustion calculations. For simplicity, product gas of H_2O only has been considered in this analysis.

Phenomenon of nose cone ablation in the ram accelerator tube is explained by a mathematical model given in the Section 2.1. Same model holds good for body ablation too with the difference that the ablation parameters are determined for product gas (H_2O) in that case. Projectile ablation due to its aerodynamic heating in flight up to the target is evaluated by the same model using air as the flow medium.

2.1 Modelling of Ablation Phenomenon

In this analysis all flow parameters are evaluated at the boundary layer on the projectile surface. Polynomial-based correlations of the form

$$Cp = \left(a + bt + ct^2 + dt^3 + et^4 \right) R$$

and

$$\mu = \frac{\sqrt{t}}{f + g/t + h/t^2 + i/t^3 + j/t^4}$$

are used to determine the specific heat and coefficient of viscosity of hydrogen and oxygen separately[3]. Specific heat and viscosity value of the reactant mixture ($2H_2+O_2$) is obtained by summing up the product of mass fraction and specific heat or viscosity of each gas constituent. 7 value of the mixture is given by

$$Y = Cpl(Cp - R_{mix})$$

Eucken's approximation given by Zucrow and Hoffman[3]

$$Pr = \frac{4\gamma}{9\gamma - 5}$$

and the relation

$$K = \mu Cp/Pr$$

yield the Prandtl value and the value of thermal conductivity of the mixture, respectively. Recovery factor for turbulent flow[4] is determined from the expression

$$Rf = Pr^{\frac{N+1+0.528\,M^2}{3N+1+M^2}}$$

The value of velocity profile parameter (N) is selected as 10 since Reynolds number of the flow is of the order 10^9. The projectile wall temperature is given by

$$t_{wall} = t\left\{1 + Rf\left(\frac{\gamma-1}{2}\right)M_l^2\right\}$$

and the average Nusselt number for the turbulent flow is approximated from the well-known formulation.

$$Nu = 0.036\, Re^{0.8}\, Pr^{0.33}$$

where Re is obtained from the relation

$$Re = \rho\, M \sqrt{\gamma R_{mix} t}\;\; lc/\mu$$

Average heat transfer coefficient is evaluated from the expression

$$hc = K Nu/lc$$

Chilton-Coulburn analogy[5] relates the coefficients of heat and mass transfer by the relation

$$mc = hcl(p \;\; CpLe^{2/3})$$

Mass transfer rate is worked out from the expression, $mt = mc.sa.\xi$, neglecting the concentration of ablatant in free stream of gases. Since it is reasonably accurate to assume the temperature of ablatant vapours equal to the projectile wall temperature, value of ξ is obtained from the relation,

$$\xi = \{P/(R_{abl} t_{wall})\}$$

where representative value of vapour pressure (P) corresponds to the projectile wall temperature (t_{wall}).

2.2 Analysis & Results

Geometry of a steel projectile having 25.8 mm diameter body, 14° half nose cone angle and 147 mm length coated with 19.7 g of carbon ablatant (density of 2 g/cc) on the nose cone and 28.9 g on the body (Fig. 2) is considered in the computer code developed on the mathematical model explained earlier in Section 2.1. Diameter of the projectile with ablatant coating is 33 mm. Entry velocity and Mach number of the projectile in the ram accelerator tube filled with $2H_2+O_2$ fuel-oxidiser mixture at 100 atm and 300K is 3800 m/s and 7.04, respectively. The values of specific heat (Cp), ratio of specific heats (Y), gas constant (R) and density of the mixture are 2389 J/kg K, 1.4, 692 J/kg K, and 48.42 kg/m^3, respectively. Diameter of the ram accelerator tube is taken as 38.3 mm for combustion to occur immediately behind the projectile front shoulder for maximum rearward gaseous expansion and high thrust value.

For the purpose of analysis, the flow is assumed to be in motion over the stationery projectile. The effect of boundary layer dominates the hypersonic flow regime. However, high Reynolds number due to high flow density and flow velocity in the flow regime of the ram accelerator indicates low boundary layer thickness, thereby making the flow compatible to be modelled by Taylor-Maccoll numerical technique for supersonic and irrotational conical flow[6](Fig. 1).

Combustion behind the reflected conical shock wave is modelled in accordance with steady one dimensional supersonic flow with heat transfer[7]. Reflected shock wave and the combustion zone comprise the detonation wave. The effect on the flow by expansion waves emanating at the front and rear shoulders of the projectile is modelled by the Prandtl-Mayer analysis[8].

Using the operational concepts and methodology given elsewhere[9], flow parameters and thrust values at various projectile positions in the ram accelerator tube with increment of 200 m/s in projectile velocity during in-bore travel are evaluated up to the projectile velocity of 5000 m/s at the accelerator muzzle. This data are used as input to the ablation model for determining the ablation parameters.

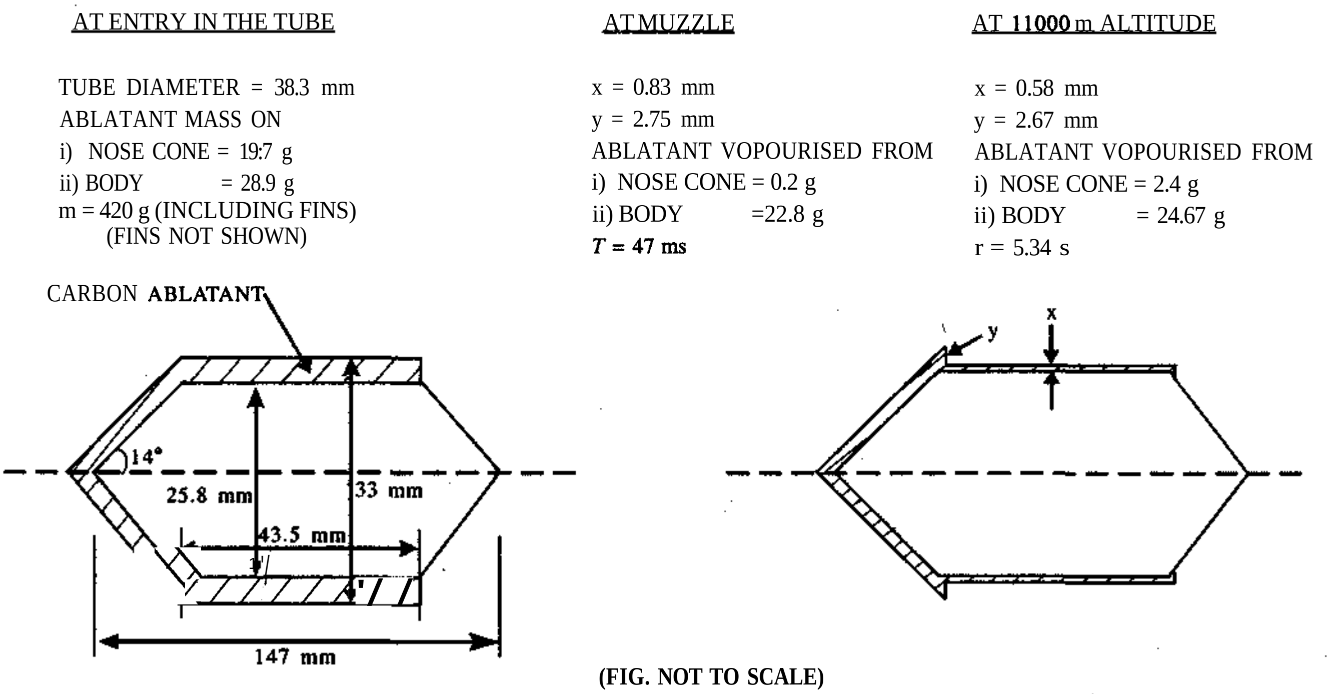

Figure 2. Projectile dimensions at accelerator tube entry, muzzle, and at 11000 m altitude

In-bore variation of temperature and Nusselt number of the flow over projectile nose cone and projectile body with the projectile Mach number is plotted in Figs 3 and 4, respectively. The effect on the projectile wall temperature(t_{wall}) is also highlighted.

Various flow and ablation parameters at projectile boundary layer corresponding to the projectile velocity of 3800 m/s and 5000 m/s, in-bore, are given in the Table 1. Selecting the Lewis number (Le) as unity for a catalytic wall, cumulative mass transfer of carbon from the projectile nose cone wall till the projectile achieves the velocity of 5000 m/s at the muzzle is equal to 0.2 g. Similarly, in-bore ablatant loss of 22.8 g from the projectile body is indicated.

Exit of the projectile from the accelerator tube and its entry into the air at 300 K changes the Mach number of the projectile from 9.26 to 14.4 (using gas constant (R) and ratio of specific heats (y) for air as 287 J/kg K and 1.4, respectively). Flow in the conical shock envelope formed over the projectile nose cone and subsequent flow expansion over the projectile front shoulder are modelled in a similar manner as explained earlier, using air as the flow medium instead of gaseous mixture.

The computer code with 2-D equations of motion of the projectile in-flight reveals additional loss of 2.2 g of ablatant from the projectile nose cone and 1.87 g of ablatant from the body due to aerodynamic heating till the projectile reaches the combat altitude of 11000 m. During the entire analysis, carbon is assumed to sublime at 3828 K and representative pressure level of carbon vapours corresponding to the projectile wall temperature(t_{wall}) is obtained

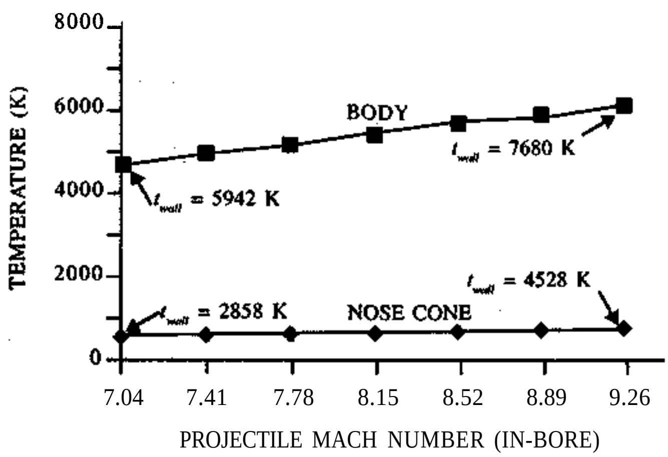

Figure 3. In-bore variation of flow temperature over projectile nose cone and projectile body with the projectile Mach number.

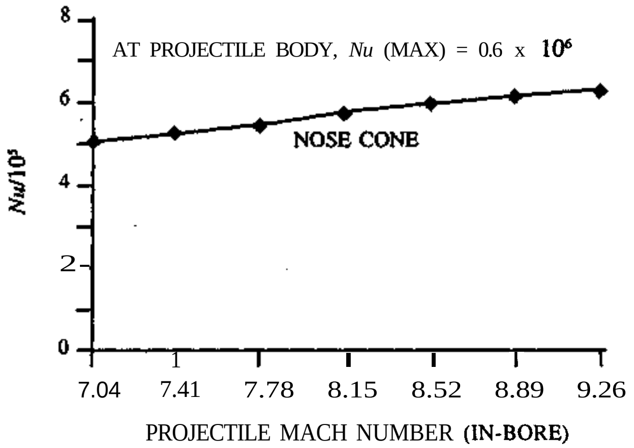

Figure 4. In-bore variation of Nusselt number of flow over projectile nose cone with the projectile Mach number.

from the constitutional diagram of carbon[10]. Assuming simple and axisymmetric ablation, projectile shape and its dimensions at the important stages of its travel in-bore and in-flight are shown in the Fig. 2.

3. ACCELERATOR TUBE LENGTH

Length of the accelerator tube to realise any projectile velocity value depends upon the amount of thrust generated by the energy released during combustion of the fuel-oxidiser mixture, followed by the expansion of gases of combustion (Fig.1). Thrust value consistently increases along with the travel of projectile in the tube. Knowing the maximum thrust value, ie, the value corresponding to the projectile position at the accelerator muzzle and on assuming a linear increase in the thrust value from the point of projectile entry in the accelerator tube up to the muzzle, the tube length is determined from the equation as

$$1/2\varepsilon\left(m_m V_m^2 - m_e V_e^2\right) = 1/2(F.L)$$

where e accounts for heat losses. The above equation is based on the fact that the energy required to increase the velocity of the projectile up to the muzzle value is given by the shaded area as shown in the Fig. 5. Maximum thrust value corresponding to the projectile muzzle velocity of 5000 m/s is found to be 53371 N for the projectile configuration already elucidated in section 2.2, operating in the ram accelerator tube of 38.3 mm diameter filled with the fuel-oxidiser mixture of $2H_2 + O_2$ at 100 atms. Ram accelerator tube length required to achieve the projectile muzzle velocity value is 72 m. Accuracy of this value can further be improved by including effect of exact thrust values at various locations of projectile travel in ram accelerator tube during computations. The shaded area (Fig. 5) or the right hand side term of the above equation can then be evaluated by any numerical integration technique like trapezoidal or Simpsons 1/3 rule.

Tube length of the ram accelerator can be reduced by increasing the thrust value, which is possible using energetic gaseous fuels possessing higher heats of combustion. However for a given fuel-oxidiser mixture, reduction in tube length of the ram accelerator is possible either by increasing the diameter of the ram accelerator tube or by increasing the filling pressure of the fuel-oxidiser mixture in the tube.

The effect of increase in tube diameter on the tube length is found (Table 2). Excessive increase in tube diameter, however, can lead to problem of

Table 1. Various flow and ablation parameters at projectile boundary layer corresponding to the projectile velocity of 3800 m/s and 5000 m/s, in-bore

Projectile velocity & Mach number	Part of the projectile	M	Cp (J/kg K)	μ (Ns/m²)	y	Pr	K (W/mK)	Rf	$Re/10^9$	hc (W/m²K)	mc (m/s)	mt (kg/s)
3800 m/s, 7.04	Nose cone	4.87	2495	0.000029	1.38	0.740	0.099	0.87	1.30	367150	0.96	0.000
	Body	1.88	3272	0.000168	1.16	0.850	0.645	0.94	0.09	558075	3.95	0.504
5000 m/s, 9.26	Nose cone	5.66	2542	0.000036	1.37	0.746	0.121	0.87	1.60	553879	1.18	0.078
	Body	1.8	3385	0.000218	1.15	0.854	0.864	0.94	0.09	810328	4.40	0.472

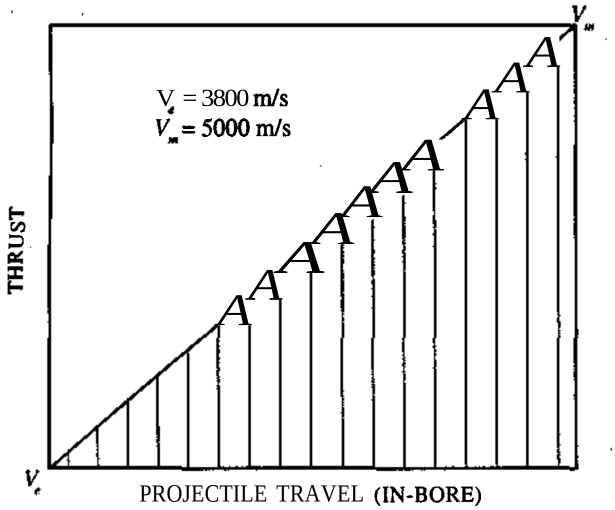

Figure 5. Energy responsible for projectile acceleration, in-bore.

Table 2. Thrust and accelerator tube length values for various tube diameter and filling pressure configurations

Tube diameter (mm)	Filling pressure (atms)	Thrust at muzzle, F (N)	Tube length, L (m)	
			(ε=1)	(ε = 0.5)
38.3*	100	53371	72	144
50**	100	91894	44	88
38.3***	200	106743	37	74
50****	200	183788	22	44

Diameter of ablatant coated projectile = 33 mm
Length of projectile body = 43.5 mm
m_e = 420 g (including fins)
* m_m = 397 g , z_m = 6.4 mm
** m_m = 406 g , z_m = [illegible]8 mm
*** m_m = 402 g , z_m = 6.4 mm
**** m_m = 409 g , z_m = 28.8 mm
V_e = 3800 m/s , V_m = 5000 m/s

in-bore instability of comparatively smaller projectile. Also, increase in diameter is restricted by the requirement of formation of detonation wave preferably in the vicinity of the front shoulder of the projectile, or at the most, on the projectile body for maximum thrust condition. Shift in the detonation wave end (intersection point of detonation wave and the expansion wave) from the projectile front shoulder with increase in tube diameter is given in Table 2. The effect of increase in filling pressure of fuel-oxidiser mixture on the ram accelerator tube length is also investigated with the same projectile parameters. Excessive filling pressure, however, can lead to premature ignition of the gaseous mixture by compression of flow gases in the region between the nose cone of the projectile and the tube wall. Premature ignition causes the projectile to force its way against the gases of combustion on the nose cone, thereby resulting in reduced or negative thrust.

Suitable end-closure mechanism is required to hold the fuel-oxidiser mixture filled at high pressure in the ram accelerator tube. Thick mylar diaphragms can result in damage due to the projectile-diaphragm impact besides disturbing the in-bore ballistics of the projectile. Other devices like explosively removed closures and fast acting mechanical valves operating on high pressure gas must open at the right time after the projectile enters into the ram accelerator tube. This can lead to catastrophic damage in case these devices fail to open at the right moment. An aero-window supported by mechanical valves and thin diaphragms is an ideal end-closure device (Fig. 6).

In an aero-window, ram accelerator tube fitted with thin light diaphragms at its ends is loaded with the drive fuel-oxidiser mixture, while air is simultaneously loaded between the diaphragms and the closed mechanical valves at a pressure equal to the pressure of the drive mixture to keep the pressure balance across the thin diaphragms to negligible limits. The aero-windows are then started to supply high pressure air needed to balance the pressure across the mechanical valves. The mechanical valves are opened after balancing the pressure. The projectile is finally launched into the ram accelerator tube after ensuring that the valves are fully open.

3.1 Modelling of an Aero-window & Results

High pressure air with Mach number less than unity is supplied to the nozzle of the aero-window at region 1(Fig. 7). Conventional governing equations given below, for isentropic and steady one-dimensional flow in a nozzle, are used to model the flow up to the throat shown as region 2 (Fig. 7). The flow is accelerated to Mach number of unity at the throat and so M_2 is taken as unity in these equations. Equations of similar nature are used for the divergent

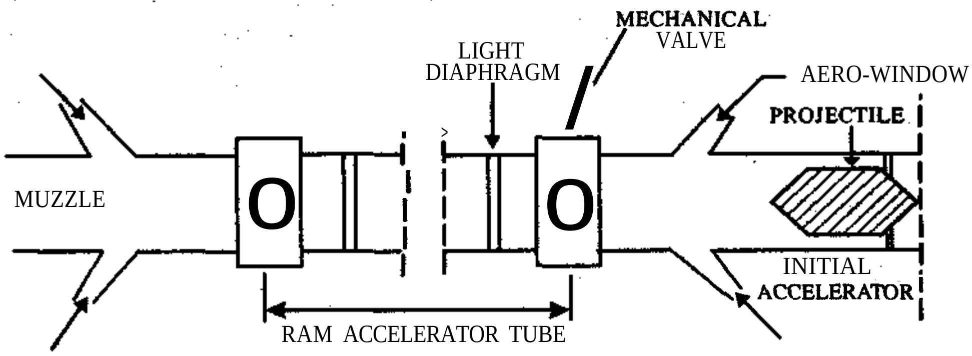

Figure 6. Schematic of an aero-window as a tube end closure device

portion of the nozzle from region 2 (Fig. 7) up to the region 3 (Fig. 7).

$$\frac{p_2}{p_1}=\frac{\left(1+\frac{\gamma-1}{2}M_1^{\,2}\right)^{\frac{\gamma}{\gamma-1}}}{\left(1+\frac{\gamma-1}{2}M_2^{\,2}\right)^{\frac{\gamma}{\gamma-1}}}$$

$$\frac{t_2}{t_1}=\frac{\left(1+\frac{\gamma-1}{2}M_1^{\,2}\right)}{\left(1+\frac{\gamma-1}{2}M_2^{\,2}\right)}$$

$$\frac{\rho_2}{\rho_1}=\frac{\left(1+\frac{\gamma-1}{2}M_1^{\,2}\right)^{\frac{1}{\gamma-1}}}{\left(1+\frac{\gamma-1}{2}M_2^{\,2}\right)^{\frac{1}{\gamma-1}}}$$

$$\rho_2A_2\sqrt{\gamma R t_2}\,M_2=\rho_1A_1\sqrt{\gamma R t_1}\,M_1$$

where R (for air) = 287 J/kg K

and γ (for air) = 1.4.

An expansion fan originates at the convex corner at the interface of the nozzle and the ram accelerator

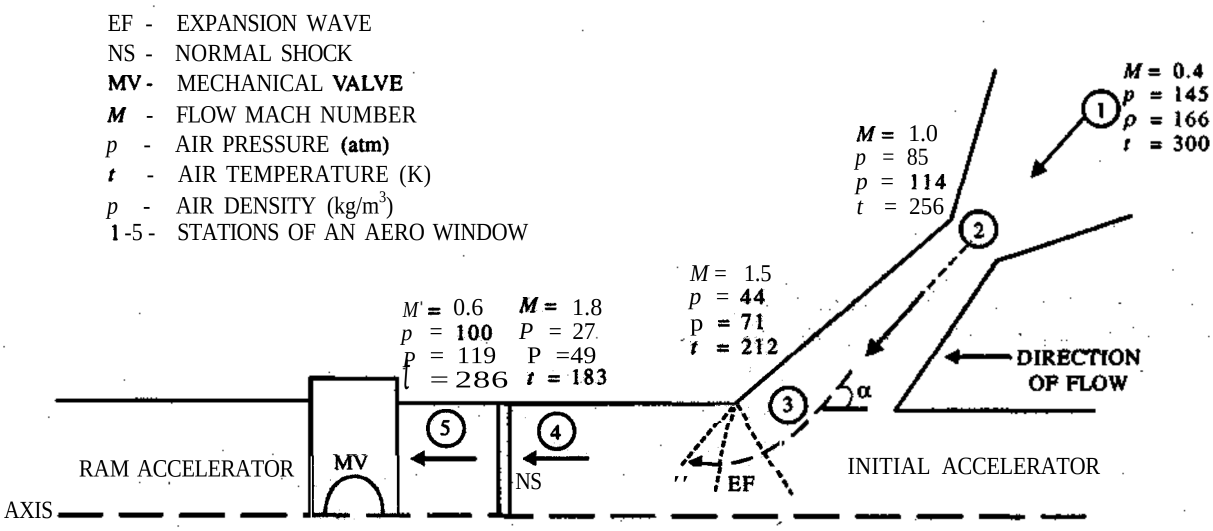

Figure 7. Flow processes and sample values of flow parameters at different stations of an aero-window.

tube which increases the **Mach** number of the flow in region 4 (Fig. 7). The expansion fan is replaced by a discrete wave and **Prandtl-Mayer** analysis is used to **model** the flow expansion. Prandtl-Mayer angle related **to** the Mach number of flow in region 3 is read from the flow expansion data tables. New value of Prandtl-Mayer angle given by equation $\upsilon_4 = \upsilon_3 + a$ enables to determine the corresponding Mach number in region 4. The values of stagnation temperature and pressure before and after expansion are the same, which lead to evaluation of all the remaining flow parameters in region 4. Pressure jump across the normal shock increases the flow pressure. Flow parameters in region 5 are determined by conventional normal shock relationships. The values of all important flow parameters at different stations of an aero-window with the nozzle drive pressure of 145 atm. **are** given in Fig. 7. *a* for the nozzle is chosen as 10° and M_1 is selected as 0.4. For ram accelerator tube diameter of 38.3 mm, mass flow rate **for** $\frac{A_2}{A\otimes}$ ratio of 0.075 is 3.16 kg/s.

4. ACCELERATOR STARTING VELOCITY

The projectile needs to enter the accelerator tube with sufficient velocity to initiate a conical shock wave and its reflection of sufficient strength from the tube wall to cause self-ignition of the **fuel-oxidiser** mixture. The value of this velocity for $2H_2+O_2$ mixture under study is 3800 **m/s**. Velocity of such a magnitude can neither be delivered by conventional gas guns nor by tested technology of thermally choked ram accelerators. This problem is overcome by modifying the design of the projectile to initiate boundary layer ignition. The reflected shock wave from the tube wall **(Fig.1)** does not strike the projectile surface and is neutralised, to a maximum extent, by an expansion wave produced at the front convex shoulder of the projectile. Modification of the projectile by replacing its front convex shoulder by a steep ramp produces one more shock wave instead of an expansion wave. The effects of original reflected shock wave from the tube wall, therefore, continue uninterrupted up to the projectile body, leading to the separation of boundary layer of flow at the projectile **surface,** which triggers combustion. Combustion in this manner has been reported in $2H_2 + O_2 + Ar$ **mixture**[11] with the projectile velocity as low as 2130 **m/s**. But **unstart** condition or upstream propagation of the combustion front up towards the projectile nose cone is quickly reached in $2H_2 + O_2 + Ar$ mixture since the projectile velocity of 2130 **m/s** is less than the detonation velocity of the mixture. Unstart condition results in negative thrust, and therefore, is not desirable.

To maintain the positive thrust for longer duration, the modified projectile must enter the accelerator tube with the velocity at least equal to the detonation velocity of the gas mixture. This value for $2H_2 + O_2$ mixture is 2800 **m/s**. Velocity of 2800 **m/s** lies within the output range of a three- stage thermally-choked ram accelerator tube **with** the **length**[12] of 15m. Operating velocity for thermally-choked ram accelerator is 1500 **m/s**, which can be obtained from conventional launch gun having length of the order of few meters. A possible schematic for achieving the projectile velocity of 5000 **m/s** with the modified projectile is shown in Fig. 8.

5. RAM ACCELERATOR IN DEFENCE-ORIENTED ROLE

Role of a ram accelerator when employed against fast-flying targets, like fighter aircraft, is assessed. A computer code based on 2-D equations of motion evaluates the flight parameters of the projectile at the combat altitude of **11000m**. Correction for change in atmospheric parameters with altitude is incorporated in the computer code. Angle of **launch** of the projectile is taken as 60°,

Since the accelerator cannot fire rounds in quick succession due to time-consuming gas-filling operation and other associated preparatory requirements, single-fired projectile has to be guided to ensure very high hit probability. Provision of guidance calls for higher calibre projectiles. A larger steel projectile of 100 mm calibre, 14° half nose cone angle and 1030 mm length is, therefore, considered in the computation. Diameter of the projectile with ablatant coating is 108 mm. Gas filling pressure of 100 atms. is used in the analysis. Accelerator tube of smaller diameter is required for the detonation front to form near the front shoulder of the projectile. But smaller diameter tube necessitates very large tube length, of the order of few hundred metres,

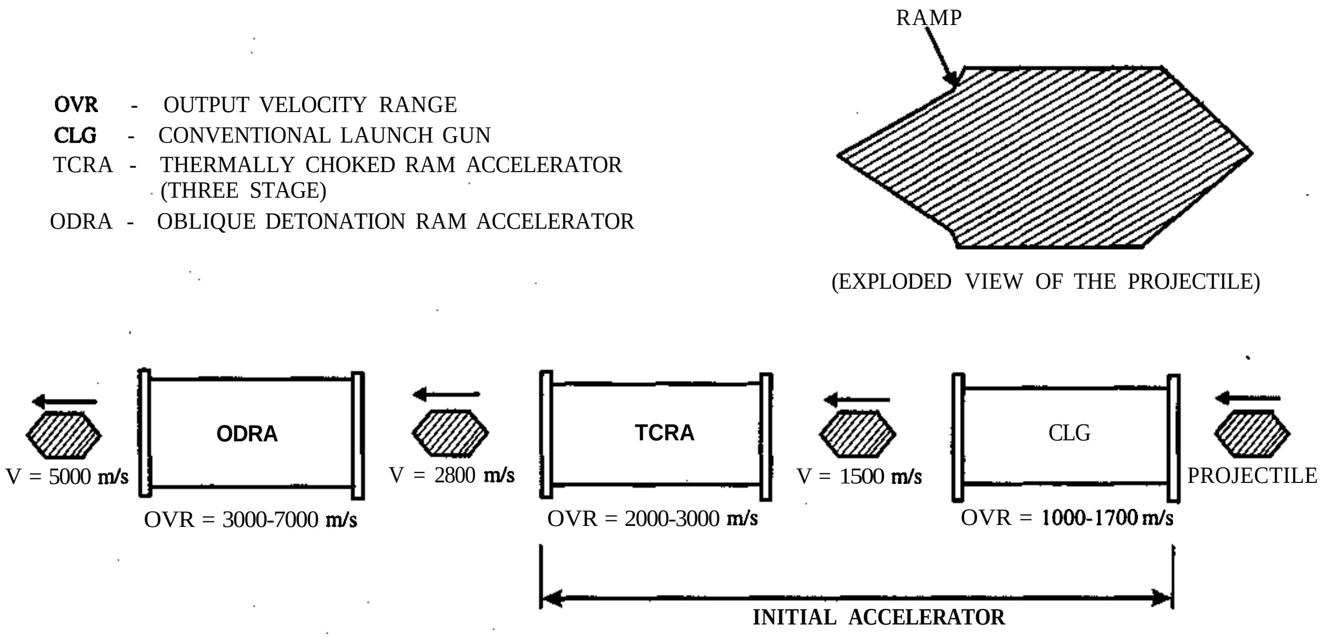

Figure 8. Schematic of launch system for achieving projectile velocity of 5000 m/s

to achieve the projectile muzzle velocity of 5000 m/s. This is avoided by selecting higher value of tube diameter, which produces detonation wave on the projectile body, resulting in slightly lower thrust value. For 400 mm tube diameter, detonation wave end is found to be at the distance of 550 mm from the front shoulder. Further increase in tube diameter prevents reflected conical shock wave to strike the projectile body, which is not desirable. It has been found that increase in the ram accelerator tube diameter up to 400 mm reduces the required tube length to 90 m (for e = 1) and cuts down the projectile ablatant thickness to 4 mm. Ram accelerator tube length can further be reduced by increasing the filling pressure up to 200 atm. Pertinent data at accelerator entry, accelerator muzzle, and at 11000 m altitude in flight are given below:

1. At entry in accelerator tube

   V = 3800 m/s

   Accelerator tube diameter = 400 mm

   Ablatant mass on

   a) Nose cone =.276 kg

   b) Body = 1.64 kg

   m = 53.91 kg (including fins)

   Coating thickness = 4 mm

   Projectile dia.(with coating) = 108 mm

2. At accelerator muzzle

   V = 5000 m/s

   Thrust, F = 6011335 N

   Ablatant vaporised from

   a) Nose cone = 0.002 kg

   b) Body = 0.985 kg

   m = 52.92 kg

   T = 54 ms

3. At 11000 m combat altitude

   V = 3782 m/s

   Ablatant vaporised from

   a) Nose cone = 0.047 kg

   b) Body = 1.146 kg

   m = 52.71 kg

   T = 3.1 s

4. Flow parameters at projectile boundarylayer corresponding to projectile velocity of 5000 m/s, in-bore

	(Projectile nose cone)	(Projectile body)
Re =	5.39×10^9	7.2×10^8
Nu =	1.6×10^6	336570
hc =	436856 W/m^2 K	607648 W/m^2K
mc =	0.937 m/s	3.30 m/s
mt =	0.667 kg/s	19.24 kg/s

5. Flow parameters at projectile boundary layer at 11000 m combat altitude

(Projectile nose cone)

Re = 3.7×10^7

Nu = 29786

hc = 3814 W/m^2 K

mc = 2.116 m/s

mt = 0.007 kg/s

A comparison of flight parameters of both small and large projectiles, discussed so far, at the combat altitude of 11000 m is displayed in Table 3. Besides high fighting Mach number of 12.48, time taken by the larger projectile to reach the combat altitude is 3.1 s, which is even less than the time taken by a conventional missile to reach the same height. Low operational time and high fighting Mach number of any guided projectile not only enhance its hit probability but also undermine the chances of enemy aircraft to maneuver and initiate counter-active measures.

Active terminal homing system can be used in the projectile to hit the target. Radome or transparent nose of the projectile made of fibre-reinforced organic resins or glass ceramics will allow passage of electromagnetic waves besides resisting aerodynamic heating. Ablatant coating will also protect the projectile nose. High melting explosive possessing good thermal stability to resist high projectile surface temperature can be used in the warhead.

Considering the overall bulk and poor mobility of the ram accelerator, the device can be permanently positioned at a strategic or vital installation on the ground which needs high level of protection from enemy air raids. A large number of ram accelerators in close proximity, positioned underground with exposed muzzles, together with the gas-filling station and other supporting equipment will enhance the effectiveness of overall weapon system.

Table 3. Comparison of flight parameters of small and large caliber projectiles at 11000 m altitude

Parameters at 11000m altitude	25.8 mm caliber projectile* with 1.8 mm thick ablatant coating	100 mm calibre projectile** with 4 mm thick ablatant coating
V (m/s)	1603	3782
M ⊕	5.30	12.48
T (s)	5.34	3.1
Range (m)	6400	6351
ϕ (degree)	59.30	59.79

Projectile muzzle velocity = 5000 m/s
* Drag coefficient ~ 0.1, m_m = 0.397 kg, m_a = 0.3929 kg
** Drag coefficient ~ 0.3, m_m = 52.92 kg, m_a = 52.71 kg
Atmospheric data at 11000 m altitude:
Pressure = 0.24 atms., Temperature = 227 K
Density = 0.36 kg/m^3, Cp = 1004 J/kg K

6. CONCLUSION & SCOPE FOR FURTHER RESEARCH

Practicability aspects of the futuristic technology of ram accelerators have been examined. Mathematical models presented indicate the following: (i) carbon coating successfully prevents projectile ablation, (ii) advent of higher energy gaseous fuels should result in reduction of accelerator tube length up to manageable limits. Under the existing conditions, increase in accelerator tube diameter and filling pressure of the fuel-oxidiser mixture minimise the tube length, and (iii) modified projectile design results in combustion at reduced projectile entry velocity in the ram accelerator tube.

Radiational effects of extremely high temperature in-bore gases of combustion on the hardware of guided projectiles and the inner surface of the accelerator tube call for detailed theoretical investigations. In-bore stability aspect of the projectile in a bigger diameter accelerator tube deserves further attention.

ACKNOWLEDGEMENT

The author acknowledges the support received from the Director, Armament Research and Development Establishment (ARDE), Pune, during the course of this work

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