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Modelling of Ram-Accelerator Flow Fields

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ABSTRACT

Dynamic phenomena in 'ram-accelerator', a ramjet-in-tube concept for accelerating projectiles to ultra high velocities, have been investigated analytically and compared with the experimental investigations reported in open literature. The projectile resembles the centrebody of a conventional ramjet, but travels through a stationary tube filled with a mixture of gaseous fuel and oxidizer. The energy release process travels with a projectile inside the accelerator tube. The characteristics of subsonic combustion, thermally-choked mode of propulsion, which is capable of increasing the velocity up to Chapman-Jouguet (C-J) detonation velocity of the propellant mixture used in ram-accelerator tube, have been studied. The ram-accelerator with a fixed diffuser area ratio operates with different initial velocities for different propellant mixtures. Propellant mixture with CO_2 as diluent is used for velocity range ~ 770-1150 m/s; propellant mixture with nitrogen as diluent is used for velocity range ~ 925-1450 m/s and that with helium as diluent is used for velocity range ~1500-2000 m/s. Mixtures of propellants with different diluents in varying degree of proportions, giving rise to different acoustic and C-J detonation speeds, have been investigated to evaluate their suitability in the ram-accelerator divided into several segments.

NOMENCLATURE

a	Speed of sound
A	Flow cross-sectional area
c_p	Specific heat at constant pressure
F	Thrust
h	Specific enthalpy
m	Mass of the projectile
$\overset{o}{m}$	Mass flow rate
$\overline{m}$	Molecular weight
M	Mach number
p	Static pressure
P	Stagnation pressure
R	Characteristic gas constant
t	Static temperature
T	Stagnation temperature
V	Velocity vector
ϕ	Area ratio in the sudden expansion process; thrust-pressure ratio
γ	Ratio of specific heats
η	Ballistic efficiency
ρ	Density
Δ_q	Heat of reaction

Subscripts

1	Entry to the accelerator tube
2	Downstream of the conical shock
3	Downstream of the normal shock
4	Downstream of the sudden expansion process
5	Downstream of the combustion process

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1. INTRODUCTION

1.1 Concept of Ram-Accelerator

Ram-acceleration is a promising new technique by which relatively large masses (up to 1000 kg) can, in principle, be accelerated efficiently to velocities up to 12 km/s by using chemical energy in a new manner. In the ram-accelerator shown in Fig. 1, a projectile similar in shape to the centrebody of a ramjet engine is injected at high speed into a tube filled with a combustible gaseous mixture. As the projectile moves into the tube under supersonic conditions, the shocks occur on and around the projectile. If the gases ignite, the combustion around or behind the projectile can be self-sustaining. The net effect is to generate a localised high pressure region around and behind the projectile which produces acceleration[1].

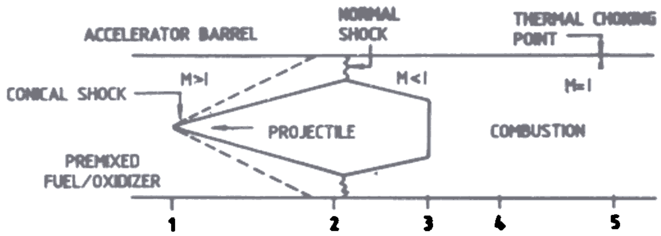


Figure 1. Schematic of subsonic combustion thermally-choked mode of ram-accelerator.

1.2 Modes of Ram-Accelerator

Various modes of ram-accelerator operation, which span the velocity range 0.7-12 km/s have been developed and studied. These can be classified as subsonic and supersonic combustion modes. The ram accelerator can also be classified as subdetonative, transdetonative and superdetonative detonation drive modes. The subsonic combustion ram-accelerator drive mode can be either mechanically or thermally choked. The projectile is injected into the accelerator tube at a particular velocity by a conventional powder or gas gun. The gas mixture in the accelerator tube is chosen in such a way that the projectile Mach number is initially in the range 2.5-3. The cone angle of the nose is such that the oblique shock system in the diffuser does not initiate combustion. A normal shock is located downstream of the projectile throat, which is not strong enough to initiate combustion. In the thermally-choked mode, the combustion zone is established behind the projectile, and the choking of flow by the heat release stabilises the normal shock on the projectile. The combustion is initiated by either an onboard ignitor or an external ignitor mounted on the launch tube. The projectile velocities are limited to about 3 km/s. The mechanically-choked subsonic combustion ram-accelerator mode and other supersonic combustion modes are well documented in open literature[2].

1.3 Applications of Ram-Accelerator

The ram-accelerator, due to its unique principle of operation, has the potential for a large number of applications. It has the potential to enhance the capabilities of current gun technology. It offers high muzzle velocity and programmable acceleration. In a constant area tube, the ram-accelerator propulsive cycles do not generate recoil, and by properly venting the entrance to the accelerator tube, the exhaust gases emerge as a rearward-directed jet which can be used to eliminate the recoil of a conventional gun prelauncher[3]. The ram-accelerator, as a chemically-propelled mass driver, is a viable new approach for directly launching acceleration-insensitive payloads into a low earth orbit[4].

1.4 Scope of Work

Hertzberg[1], *et al.* carried out a control volume analysis for the thermally-choked mode of ram-accelerator without considering the details inside the control volume, such as flow through conical shock and normal shock, subsonic diffusion, flow through sudden enlargement, combustion, and subsequent acceleration of the products to sonic speed. The present analysis focuses attention on the details of the flow in the thermally-choked mode of ram-accelerator. The results are in close confirmity with the experimentally investigated trends reported by Hertzberg[1], *et al.* and the exact matching could not be obtained as the input data reported by them are incomplete.

2. FLOW & COMBUSTION MODELLING OF THERMALLY-CHOKED MODE

Advances in computational techniques and experimental methods have renewed interest in the development of mathematical models for analytical study of fluid-flow behaviour of various processes. The thermally-choked subsonic combustion mode has been modelled for evaluating the suitability of various propellant mixtures over velocity ranges of interest. The theoretical model is basically divided into two main modules, diffuser flow module and combustion module. The diffuser flow module is further subdivided into conical shock, normal shock, isentropic flow and sudden expansion process submodules.

2.1 Conical Shock Phenomenon

The conical shock at the tip of the projectile is governed by the Taylor-Maccoll flow around the cone[5]. Since upstream flow is supersonic, a shock wave is formed in the flow. The pressurised gas mixture in the accelerator tube is so chosen that the projectile Mach number is initially sufficient for diffuser to start. The cone angle of the projectile is such that the oblique shock system in the diffuser does not initiate combustion. When the semicone angle and free-stream Mach number fall within certain limits, the shock wave is attached to the vertex of the cone.

2.2 Normal Shock Phenomenon

The normal shock is assumed to occur at the minimum cross-sectional area of the centrebody downstream of the conical shock. The flow through the normal shock wave is analysed by considering one-dimensional flow through the portion of the centrebody downstream of the cone, using the standard gas dynamic relationships pertaining to normal shock wave[6] The location of normal shock is governed by the projectile Mach number and the heat release in the combustion zone. The lower limit to the projectile Mach number is predicted by the condition when the normal shock stands just at the diffuser throat. This limit is a function of the ratio of the diffuser throat area to the tube cross-sectional area and the heat of combustion, Δq.

2.3 Isentropic Flow Phenomenon

The flow downstream of the conical shock to just upstream of the normal shock and the flow downstream of the normal shock till the base of the projectile are treated by standard one-dimensional isentropic flow equations[6].

2.4 Sudden Expansion Process

The flow from the base of the projectile till it attains the full tube cross-section is modelled as a flow through sudden enlargement process[7]. The governing equations are:

Conservation of mass:

$$\dot{m} = \rho_3 A_3 V_3 = \rho_4 A_4 V_4 \tag{1}$$

Conservation of momentum

$$p_3 A_3 + p_3'(A_4 \quad A_3) - p_4 A_4 = \overset{o}{m}(V_4 - V_3) \tag{2}$$

Conservation of energy

$$\frac{t_3}{t_4} = \frac{2+(\gamma-1)M_4^2}{2+(\gamma-1)M_3^2} \tag{3}$$

On combining these equations in terms of perfect gas equation of state, the following equation is obtained:

$$\frac{M_4(2+\gamma-1)M_4^2)^{1/2}}{1+\gamma M_4^2} = \frac{M_3(2+(\gamma-1)M_3^2)^{1}}{1+\gamma M_3^2 + (p_3'/p_3)\,(\frac{1-\phi}{\phi}} \tag{4}$$

where $\phi = A_3/A_4$, the area ratio.

For a subsonic case, the ratio p'_3/p_3 is considered to be unity, i.e.,

$$\frac{p_3}{p_3} \quad subsonic \tag{5}$$

The total pressure ratio across a sudden enlargement is given by

$$\frac{p_4}{p_3} = \phi\left[\frac{M_3}{M_4}\right]\left[\frac{2+(\gamma-1)M_4^2}{2+(\gamma\ \ 1)M_3^2}\right]^{\frac{\gamma+1}{2(\gamma-1)}} \qquad (6)$$

Similarly, the static pressure ratio is given by

$$\frac{p_3}{p_4} = \frac{1}{\phi}\left[\frac{M_4}{M_3}\right]\left[\frac{2+(\gamma-1)M_4^2}{2+(\gamma-1)M_3^2}\right]^{1/2} \qquad (7)$$

2.5 Combustion Process

It is assumed that the combustion occurs in the full tube area beginning just beyond the base of the projectile where sudden expansion process terminates. The heat release process is treated by a conventional constant area heat addition analysis coupled with equilibrium chemistry. The heat release reaches a thermal choking condition at some distance behind the projectile. This stabilises the normal shock on the projectile, resulting in forward thrust. The heat release of combustion, Δ_q is determined from the difference in the enthalpy of formation between the unreacted propellant mixture and the combustion products in chemical equilibrium at sonic velocity w.r.t. the projectile. The properties, as a result of combustion of the reactant mixture downstream of the projectile have been evaluated by NASA-CEC-71 software package[8]. The flow acceleration of the products of combustion to sonic velocities (thermally-choked mode of combustion) has been evaluated by treating it as a Rayleigh heat addition process[6].

2.6 Performance Parameters

For the ram-accelerator, the performance of the device can be evaluted by two main parameters: thrust-pressure ratio and ballistic efficiency. The thrust-pressure-ratio is the net average drive pressure on the projectile (the thrust divided by the maximum projectile cross-sectional area) divided by the maximum cycle pressure. This ratio is an important performance parameter because it provides a measure of the launch capability of the device w.r.t. the maximum pressure the projectile and the launch tube must survive. The ballistic efficiency is defined as the rate of change of projectile kinetic energy divided by the rate of heat addition to the flow[2].

The nondimensional thrust on the projetile is expressed as:

$$\frac{F}{p_1 A} = \frac{p_5}{p_1}(1+\gamma_5\ \ -(1+\gamma_1 M_1^2) \qquad (8)$$

where F is the thrust, A is the tube cross-sectional area, p_1 and p_5 are the static pressures entering and leaving the control volume, γ_1 and γ_5 are the specific heat ratios before and after the combustion and M_1 is the Mach number of the flow entering the control volume. At the thermal choking point, $M_5 = 1$. The heat of reaction of the propellant gas mixture, Δ_q is given by

$$\Delta_q = c_{p5} T_5 - c_{p1} T_1 \qquad (9)$$

where c_{p1} and c_{p5} are the specific heats at constant pressure and T_1 and T_5 are the stagnation temperatures before and after combustion, respectively.

Also,

$$\frac{p_5}{p_1} = M\left[\frac{\gamma_1 \overline{m}_1 t_5}{\gamma_5 \overline{m}_5 t_1}\right]^1 \qquad (10)$$

and

$$\frac{t_5}{t_1} = \frac{T_5}{T_1}\left[\frac{2+(\gamma-1)M_1^2}{\gamma_5+1}\right] \qquad (11)$$

where $t_1, p_1, \overline{m}_1$ and $t_5, p_5, \overline{m}_5$ are the static temperature, static pressure and molecular weights at station 1 and station 5, respectively.

Substituting Eqns (9-11) in Eqn (8) yields

$$\frac{F}{\;} = \frac{\gamma_1 M_1}{\;}\left[\left(\frac{\gamma_5^2 - 1}{\gamma_1 - 1}\right)\left(+ \frac{\gamma_1 - 1}{2} M_1^2 + \frac{\Delta_q}{c_{p1} t_1}\right)\right.$$
$$-(1 + \gamma_1 M_1^2) \qquad (12)$$

Combining Eqn (12) with the equation of motion

$$\frac{du_1}{dx} = \frac{F}{mu_1} \qquad (13)$$

and integrating yields the velocity, u_1 of the projectile of the mass, m as a function of position x along the launch tube. As the projectile accelerates, M_1 increases and the thrust decreases, reaching zero at a flight Mach number given by

$$M_1 = [(\alpha - \sqrt{\alpha^2 - \beta})/\beta]^{1/2} \qquad (14)$$

where,

$$\alpha = \left[\frac{\gamma_1}{\gamma_5}\right]^2 \left[\frac{\gamma_5^2 - 1}{\gamma_1 - 1}\right]\left[1 + \frac{\Delta_q}{c_{p1} t_1}\right] - \gamma_1$$

and

$$\beta = \left[\frac{\gamma_1}{\gamma_5}\right]^2$$

This corresponds to the Mach number of a one-dimensional C-J detonation wave propagating in the same gas mixture. Thus, in the absence of friction, the limiting velocity of the thermally-choked mode of propulsion is the C-J detonation velocity. The maximum thrust occurs at

$$M_1 = \left[\left(\frac{\gamma_5 - 1}{\gamma_1 - 1}\right)\left(1 + \frac{\Delta_q}{c_{p1} t_1}\right)\right] \qquad (15)$$

Substituting the above expression in the Eqn (12) yields maximum thrust given by

$$\left[\frac{F}{p_1 A}\right]_{max.} = \frac{\gamma_1(\gamma_5 - 1)}{\gamma_5(\gamma_1 - 1)}\left[1 + \frac{\Delta_q}{c_{p1} t_1}\right] - 1 \qquad (16)$$

The ballistic efficiency is calculated by the expression

$$\eta = \left[\frac{F}{\;}\right]\frac{a_1^2}{\gamma_1 \Delta_q} \qquad (17)$$

where a_1 is the speed of sound given by

$$a_1 = \sqrt{\gamma_1 R_1 t_1} \qquad (18)$$

The thrust pressure ratio ϕ is given by

$$\phi = \frac{F}{\;} = \left[\frac{F}{\;}\right]\left[\frac{p_1}{p_4}\right]\frac{A}{A_p} \qquad (19)$$

where A_p is the maximum projectile cross-sectional area and p_4 is the maximum pressure in the cycle.

Clearly, the key to optimum performance is to keep the projectile Mach number within a narrow range, close to that corresponding to the peak thrust and efficiency. This can be accomplished by having a graded propellant mixture with a speed of sound that increases towards the muzzle of the launch tube, or by dividing the launch tube into several segments filled with different propellant mixtures, and constraining the projectile to operate in a limited Mach number range in each segment, as shown in Fig. 2.

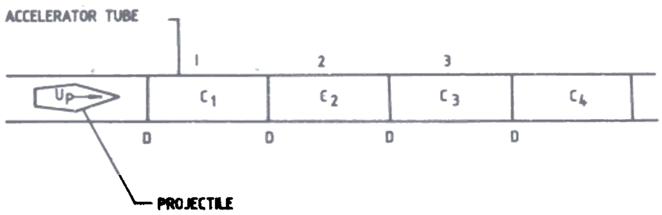


Figure 2. Schematic of multistage ram-accelerator. D: Diaphragms $c_4 > c_3 > c_2 > c_1$ where c_n is the speed of sound in stage n.

3. CASE STUDY

A detailed analysis of the thermally-choked mode of ram-accelerator has been carried out using the configuration and test data reported by the researchers at the University of Washington[1]. A computer software has been developed to carry out

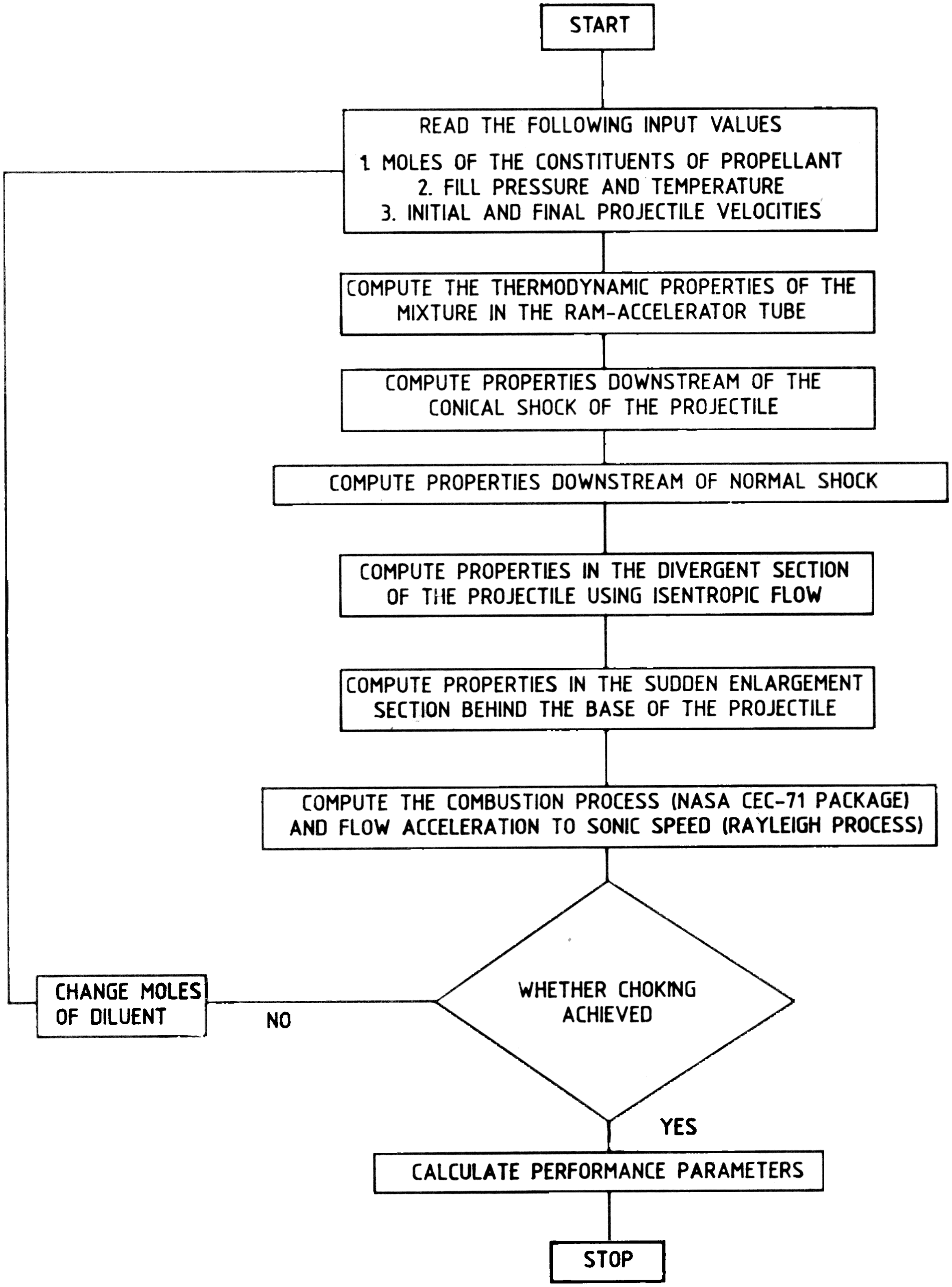


Figure 3. Flow chart for the flow field analysis

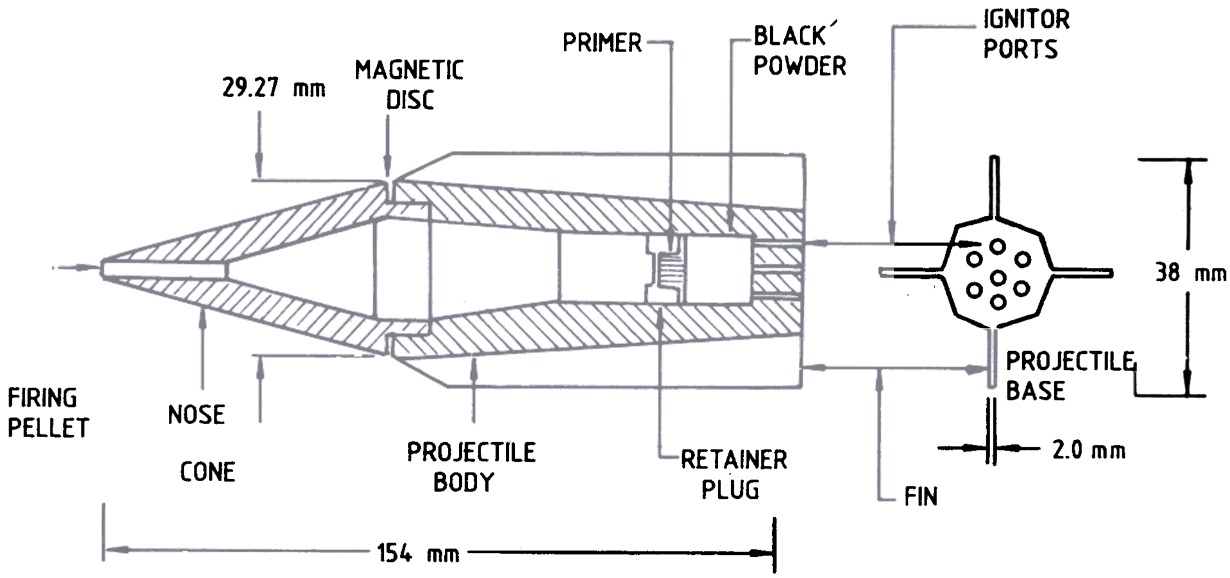


Figure 4. Cross-section of the ram-accelerator projectile

the performance computations of the ram-accelerator flow field for various propellant combinations. The flow chart depicting the computer model is shown in Fig. 3. In the ram-accelerator facility set up by the researchers at the University of Washington, the principal components are: single-stage light gas gun, ram-accelerator section, final dump tank, and projectile decelerator. Associated subsystems are: gas handling system, instrumentation, and data acquisition system. The projectile geometry considered for the analysis is illustrated in Fig. 4. The length of the projectile is 154 mm and its maximum diameter is 29.27 mm, which results in a diffuser area ratio of 1.9072. The base diameter is

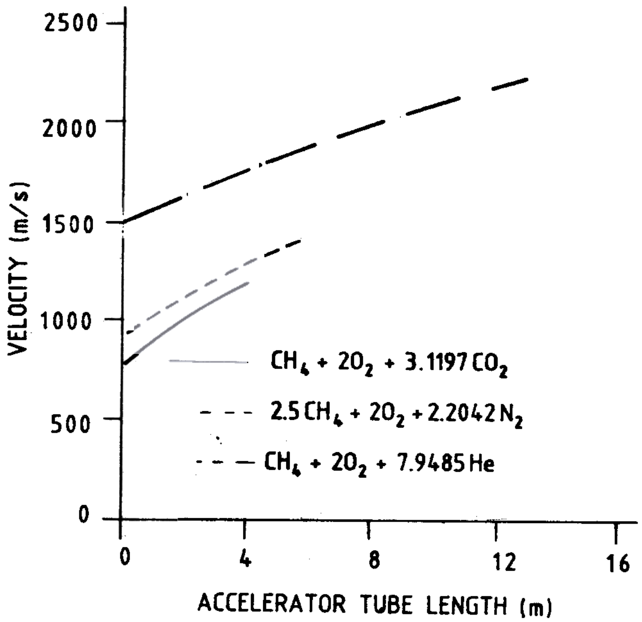


Figure 5. Variation of projectile velocity with accelerator tube length requirement.

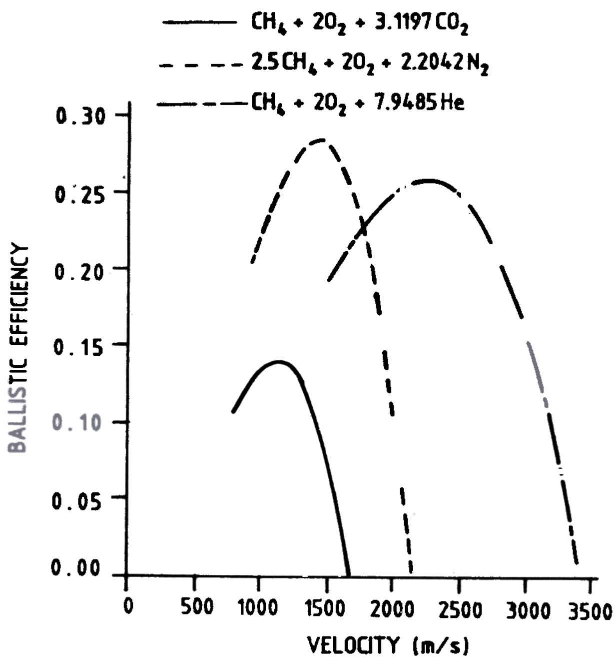
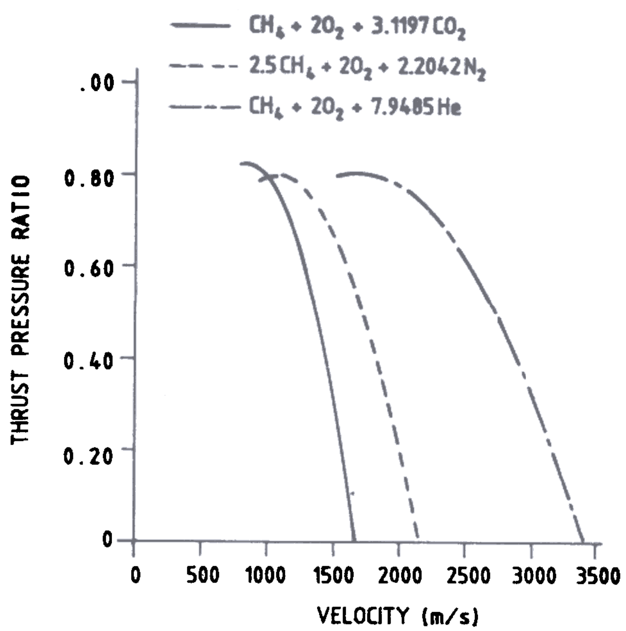


Figure 6. Variation of ballistic efficiency with projectile velocity.



7. Variation of thrust-pressure ratio with projectile velocity.

18 mm. The total mass of the projectile with obturator considered is 100 g. The semicone angle of the nose of the projectile is 10°.

4. RESULTS & DISCUSSION

4.1 Operating Conditions

The experiments by various researchers till date have been carried out using methane and oxygen as fuel and oxidiser, and carbon dioxide, nitrogen, helium and excess methane as diluents. Three types of mixtures have been arrived at, based on the present theoretical analysis, in the increasing order of the velocity range. In the lowest velocity range (770-1150 m/s), the mixture used is $CH_4 + 2O_2 + 3.1197\ CO_2$. The mixture used in the higher velocity range (925-1450 m/s) is $2.5\ CH_4 + 2O_2 + 2.2042\ N_2$. In the still higher velocity range (1500-2250 m/s), the mixture used is $CH_4 + 2O_2 + 7.9485\ He$. The theoretically calculated mixtures are slightly different from the mixtures considered for experimental purposes by Hertzberg[1], *et al.*, as the experimental mixtures do not produce choking condition after complete combustion. This may be the limitation of the present model. The use of carbon dioxide, nitrogen, helium and excess methane as diluent serves two purposes: (i) it tailors the speed of sound of the mixtures so that the initial projectile Mach number exceeds the minimum required to start the diffuser, and (ii) it minimises the possibility of the combustion wave developing into a detonation[9]. The above-mentioned mixtures are used with the propellant fill pressure of 12 atm, diffuser area ratio of 1.9072 and the ambient temperature of 298.15 K.

4.2 Pressure Record

In the diffuser section, the pressure keeps on increasing and peak pressure occurs somewhere behind the projectile. The decay in pressure following the peak is due to the heat addition and choking of the flow and the subsequent expansion of the combustion products into the tube behind the choking point. The calculated ratio of peak pressure to the tube fill pressure is ~15.8 for the nitrogen diluted mixture, ~16.4 for the carbon dioxide diluted mixture, and ~17.0 for the helium diluted mixture. The experimental pressure signatures reported in open literature are similar in shape, and the pressure ratios are similar in magnitude for the identical propellant mixtures examined till date.

4.3 Velocity Profile

The velocity of the projectile is deduced by using Eqn (12) and (13). The velocity as a function of length of accelerator tube required for the three mixtures are shown in Fig. 5. The minimum entrance velocity required with the 'slow' mixture (i.e., the one using carbon dioxide as the diluent) is ~770 m/s (M_l = 2.54). Below that velocity, an unstart condition results because the diffuser area ratio is too large for the corresponding Mach number. The 'fast' mixtures (using nitrogen and excess methane as diluents) require a minimum entrance velocity of ~925 m/s (M_l = 2.50). The velocity profiles have been made up to a maximum velocity corresponding to maximum ballistic efficiency for the relevant propellant mixture. The length of the accelerator tube required with carbon dioxide as diluent is 2.9 m for increasing the velocity from 770 m/s to 1100 m/s. The length of the tube required with nitrogen as diluent is 5.5 m for increasing the velocity from 925 m/s to 1400 m/s and for increasing the velocity from 1500 m/s to 2000 m/s with helium as diluent, the length of the accelerator tube required is 7.9 m.

4.4 Ballistic Efficiency & Thrust-Pressure Ratio

Figure 6 shows plots of ballistic efficiency as a function of projectile velocity for CH_4 + $2O_2$ + 3.1197 CO_2, 2.5 CH_4 + $2O_2$ + 2.2042 N_2, and CH_4 + $2O_2$ + 7.9485 *He* propellant mixtures. The ballistic efficiency is computed using Eqns (17) and (18). It was observed theoretically that the ballistic efficiency of nitrogen diluted mixture is significantly higher than that of carbon dioxide diluted mixture even though Δ_q is approximately. the same for both the mixtures. The peak values predicted are ~29 per cent and ~14 per cent, respectively. The experimental maxima reported by Hertzberg[1], *et al.* for nitrogen and carbon dioxide diluted mixtures are 19 per cent and 13 per cent, respectively. The trends are very much comparable in the event of difference in initial mixtures compositions between the present investigation and the experiments reported by Hertzberg[1], *et al.* The higher performance of nitrogen diluted mixture is primarily due to its higher speed of sound, on which the ballistic efficiency depends quadratically. The thrust-pressure ratio is computed from Eqn (19) using thrust and peak pressure data. Figure 7 shows plots of thrust-pressure ratio as a function of projectile velocity for the three mixtures, CH_4 + $2O_2$ + 3.1197 CO_2, 2.5 CH_4 + 2 O_2 + 2.2042 N_2 and CH_4 + $2O_2$ + 7.9485 *He*.

The experimental data on performance parameters, such as ballistic efficiency and thrust-pressure ratio with projectile velocity reported by Hertzberg[1], *et al.* shows an increasing and decreasing trend over the velocity range 700-1400 m/s. The present theoretical investigation could reproduce the experimental trend with same order of magnitude values for the performance parameters. However, exact comparison was not attempted, as the initial mixtures used in the experiments were different from those used by the present theoretical investigation.

5. CONCLUSIONS

The ram-accelerator principle is a promising and efficient concept for accelerating the projectiles from velocities of ~ 0.7 km/s to as high as ~12 km/s using chemical energy. Different modes of ram-accelerator propulsion, which in principle span this velocity range, have been presented. Of these modes, the thermally-choked, subsonic combustion mode has been studied and modelled in the present work.

Experimental investigations over the velocity range 700-1500 m/s, using methane-based propellant mixtures have established the proof-of-principle of this mode of propulsion. The experimental investigations reported in open literature are in good agreement with the trends obtained by the theoretical study made in the present work.

Propellant mixture with carbon dioxide as diluent is used for the low velocity range 770-1150 m/s; propellant mixture with nitrogen as diluent is used for intermediate velocity range 925-1450 m/s and that with helium as diluent is used for high velocity range 1500-2000 m/s. It is also concluded that below the lower limit of above-mentioned velocity ranges, an unstart condition results, due to fixed diffuser geometry considered for all the three cases of propellant mixtures.

Further, it is concluded that, as theoretical model predicts that a given propellant mixture has a maximum velocity of operation equal to its C-J detonation velocity, the acceleration of the projectile to higher velocities can be accomplished, in principle, by filling the tube with a graded propellant mixture whose C-J detonation velocity increases towards the muzzle of the tube. Since combustible mixtures with higher C-J detonation velocities tend to have higher acoustic speeds, the projectile can, in this manner, also be operated over a narrow range of Mach numbers, close to that corresponding to the peak thrust, thus achieving maximum projectile velocity in the shortest possible tube length. So, the tube can be divided into several segments, each filled with a different propellant mixture, such that the acoustic and C-J speeds of the mixtures increase towards the muzzle. In this way, the projectile can be constrained to operate over the optimum Mach number range in each segment, thus permitting the attainment of the desired high velocity with a ram-accelerator of reasonable length. Practical difficulties exist in storing various mixtures at various sections of the ram-accelerator tube, separated by diaphragms and also in proper ignition of the mixtures when the projectile travels through them. A review of the experimental work and related difficulties have been presented by Hertzberg[10], *et al.*

6. FUTURE WORK

In the present work, the reflections of shocks downstream of the conical shock and shock-boundary layer interactions have not been considered. Their inclusion is expected to provide better prediction of the flow field as the air-intake pressure recoveries are underestimated at high Mach numbers in the present model. Similarly, a theoretical study about the flow field analysis of the other modes of ram-accelerator, such as supersonic combustion modes and transdetonative and super-detonative wave modes will have to be carried out and validation by accurate experiments are to be planned.

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