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New Tube End Closure System for the Ram Accelerator

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The ram accelerator is a ramjet-in-tube device which has been demonstrated at velocities up to 2.5 km/s, has potential for operation up to ~10 km/s, and could be used for direct space launch or large ballistic ranges. The ends of the main ram accelerator tube must have end closures which support substantial pressure differences. There are potentially serious difficulties using solid end closures such as diaphragms pierced by the projectile, explosively removed end closures, or fast acting valves. These include risks of significant damage to the projectile and launch tube and the wasting of tube length. A new end closure system which uses the momentum of an annular axial air jet to support the required pressure differences is described. This system avoids the difficulties of the solid end closure system at the cost of some increase in overall launch system complexity. A preliminary design of such an air jet end closure is presented, and it is concluded that the requirements for airflow rates and storage are reasonable and would likely add only a modest increase to the overall cost of the launch system. If the difficulties with solid end closures prove to be significant, the air jet end closure system may offer a solution.

I. Introduction

AT the University of Washington, a chemical energy based ramjet-in-tube (hereafter called "ram accelerator") has been developed.[1–6] Operation of the ram acccelerator has been demonstrated experimentally[1–4,7,8] over the velocity range 0.7–2.5 km/s. These demonstrations include scaling up of the tube bore from 3.8 to 9 and 12 cm. Computational studies[2,5,6] give both one-dimensional and axisymmetric CFD solutions for the operation of the ram accelerator at velocities up to 10 km/s. The ram accelerator could be used as a launcher for ballistic ranges and for direct launch into space.[9–11]

II. End Closure Problem

The ends of the main ram accelerator tube must support significant pressure differences to contain the working gases. For the space launch system proposed in Ref. 8, this pressure difference is 50 atm. Here, we review previously used and proposed solutions to this problem.

A. Diaphragms Pierced by the Projectile

For low-velocity ram accelerator systems at tube pressures which are not too high, diaphragms pierced by the projectile are satisfactory as end closures. For example, for operation of the 3.8-cm-diam ram accelerator tube at the University of Washington at 21.4-atm pressure, Mylar diaphragms 0.0356 cm thick are required.[12] Reference 13 describes tests made in the same facility at tube fill pressures of 45 atm and velocities up to 2.58 km/s. Scaling up the diaphragm thickness of Ref. 12 to the 45 atm of the tests of Ref. 13 would lead to estimated diaphragm thicknesses of 0.0749 cm for the higher pressure operation. In the work described in Refs. 14 and 15, tests were made in a 12-cm bore facility at 51-atm fill pressures at velocities of 1.17–1.42 km/s using 1.27-cm-thick polyvinyl chloride diaphragms. Operation with projectile-pierced diaphragms under the above combinations of projectile velocity and tube fill pressure was quite satisfactory.

However, the potential for damage to projectile and launch tube will increase very rapidly as the projectile velocity increases. To some extent, diaphragm thickness (and consequently, allowable tube fill pressure) can be traded off vs projectile velocity to allow satisfactory operation with projectile-pierced diaphragms at somewhat higher velocities. That is, thinner diaphragms could be used successfully in the projectile-pierced mode at somewhat higher velocities. The disadvantage of thinner diaphragms is the lower allowable tube fill pressure and the resulting greater tube length required for a given velocity increment. Hence, for high-velocity (e.g., 5–9 km/s) operation, if reasonable tube lengths are to be used, the initial pressure in the ram accelerator tubes must be kept relatively high and relatively thick diaphragms must be used.

Scaling the diaphragm thickness of Ref. 12 to the 0.85-m tube diameter and 50-atm pressure level of the space launch system of Ref. 9 leads to a diaphragm thickness of 1.85 cm. Damage to the projectile and possibly to the tube could occur as a result of projectile-diaphragm impact, particularly at the exit (higher velocity) diaphragm. Also, at the inlet diaphragm, jamming of the relatively thick diaphragm between the projectile and the tube could cause damage.

B. End Closures Removed Prior to Arrival of Projectile

References 9 and 10 mention two types of end closures which are removed prior to the arrival of the projectile. These are explosively removed closures or fast-acting mechanical closures. The latter could be gate valves or rotary cylinder valves, possibly actuated by high-pressure gas. To keep the loss of the drive gas to any kind of a reasonable value, the end closures must be operated well after the projectile is under way. Hence, if either end closure should fail to operate properly, there is potential for catastrophic damage to the projectile and tube.

III. New End Closure Concept

A new end closure concept which avoids the problems discussed in Sec. II is as follows. Axial-flow aerodynamic windows[16] ("aerowindows") are used to support the pressure difference at the tube ends. (Transverse-flow aerowindows[17] would not be used, because the projectile, on passing through such a window, would be subject to a large side force.) No mechanical barrier is then required at the tube ends. Such a window is sketched in Fig. 1. High-pressure air is supplied to an an-

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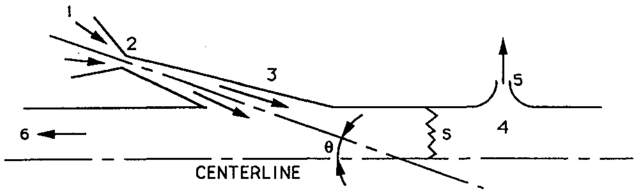

Fig. 1 Sketch of axisymmetric axial flow aerowindow. 1, 2, 3, 4, 5, and 6 denote state points for the analysis of window operation. *S* denotes shock wave. Annular drive jet enters tube at angle *θ*.

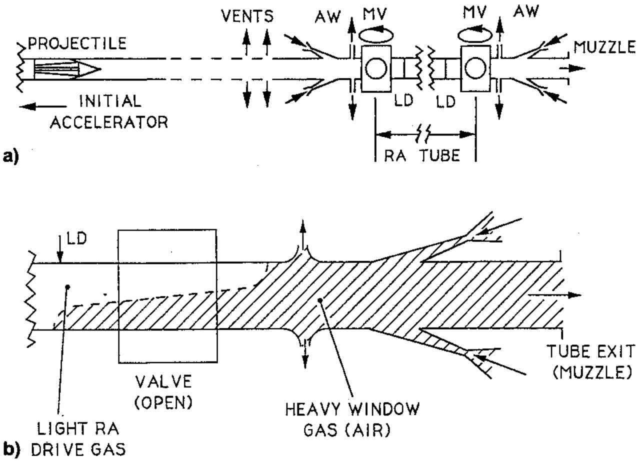

Fig. 2 Aerowindows (AW) shown in place in ram accelerator launch system: a) initial projectile accelerator is off the drawing to the left. Vents are to vent initial accelerator drive gas and gas from the aerowindow at the ram accelerator tube inlet. MV are mechanical cylinder valves. Main ram accelerator tube is denoted by RA TUBE. Light diaphragms would likely be used at points LD (see text); and b) illustrates the flowing of the heavy aerowindow gas under the lighter ram accelerator drive gas when the mechanical cylinder valve is opened and light diaphragms are not used.

nular plenum at condition 1. The flow is accelerated to typically Mach 2–3 at the annular nozzle exit (condition 3) surrounding the ram accelerator tube. The flow stagnates in region 4, and partially exhausts through the choked nozzles at condition 5. There is no flow to the right of 4. Part of the flow reverses and is assumed to be choked at condition 6. The flow from condition 6 vents to the atmosphere through the muzzle at the exit end of the ram accelerator tube and through vents in the tube wall at the inlet end of the ram accelerator tube. Since the low-pressure side of the aerowindow of Fig. 1 (state 6) vents to the atmosphere, large outflows are permissible there. This is not the case for the more usual type of aerowindow where the low-pressure side is a closed vessel at partial vacuum. It is proposed to incorporate such aerowindows into a ram accelerator system as shown in Fig. 2. In Fig. 2a, we have, from left to right, the initial accelerator (to the left of the figure), the vented tube to dump the gas from the initial accelerator and part of the flow from the first aerowindow, the first aerowindow, a moderately fast acting mechanical valve (e.g., a cylinder valve), a light diaphragm, the ram accelerator tube (with ~99.9% of its length omitted), a second light diaphragm, a second mechanical valve, and finally, a second aerowindow at the system muzzle. The mechanical valves are included because the airflow through the aerowindows is rather large, and the presence of the mechanical valve means that the aerowindows need to operate for only perhaps 10–20 s per launch.

The large, moderately fast mechanical valves are key components of the new end closure concept. Below, we estimate the opening time of such valves. A gas-actuated quarter-turn cylinder valve with a pressure rating of 200 atm, clear aperture of 2.14 cm, and opening time of 0.010 s can be purchased commercially.[18] The opening time of such devices can readily be shown to scale directly with linear dimensions. The space launch system of Ref. 11 has a tube diameter of ~85 cm. Scaling the opening time of the commercial 2.14-cm port diameter cylinder valve to a port diameter of 85 cm yields a estimated opening time of ~0.40 s for the large valve.

Light diaphragms will likely be required at points LD in Fig. 2a, just inside of the mechanical valves. Figure 2b shows a enlarged sketch of the tube exit end closure system. The end closure system is being cycled and the system is shown 1–2 s after the mechanical valve has been opened. Since the aerowindow working gas (air) is much denser than the ram accelerator drive gas near the ram tube exit, it will tend to flow under the drive gas after the mechanical valve is opened. This would produce a large side force on the projectile as it passes through the region of the mechanical valve. This side force is very undesirable and can be eliminated by placing a light diaphragm at LD. (As the ram accelerator drive gases are loaded, the volume between the light diaphragm and the mechanical valve would be loaded with air, keeping the pressure difference across the light diaphragm to very low values.) Such a light diaphragm would also most likely be required at the ram accelerator tube entrance end closure as shown in Fig. 2a.

A proposed operating sequence of the aerowindow-equipped ram accelerator is given below. An important aspect of this sequence is keeping the pressure difference across the light diaphragms small to avoid breaking them. We will assume that the light diaphragms can stand 2% of the full tube pressure and that the pressure difference across them will be limited to half this value or 1% of the full tube pressure. It is assumed that the initial accelerator is ready to fire. The mechanical valves are closed. The ram accelerator tube is loaded with the necessary drive gases while air is simultaneously loaded between the light diaphragms and the mechanical valves, keeping the pressures balanced across the light diaphragms to within 1%. Furthermore, to avoid pressure transients which could break the light diaphragms upon valve opening, the passage of the mechanical valve, which initially is isolated from the main tube, is also filled with air to within 1% of the tube pressure level. The aerowindows are started. It is assumed that the aerowindow control systems can balance the pressures across the mechanical valves in ~5 s. Upon verification that the pressures are balanced across the mechanical valves, the latter are opened. It should be possible to open gas-actuated cylinder valves in a period of 1 s or less, as estimated above. Upon verification that the mechanical valves are completely open, the projectile is launched in the initial accelerator.

The proposed system has the following advantages over the systems discussed in Sec. II. First, regarding the system of Sec. II.A, the projectile never encounters heavy diaphragms, only very light ones. Hence, the potential for projectile and tube damage due to projectile-diaphragm impact is essentially eliminated. Second, regarding the systems of Sec. II.B, the projectile is not launched until after the tube is verified to be clear of obstacles. Therefore, potentially catastrophic destructive impacts due to failure of fast opening end closures are avoided. These advantages are, however, gained at the cost of increased complexity. Two aerowindows and two mechanical valves must be provided. Systems would be required for compression and storage or generation of the air for the aerowindows. Precision control systems must be provided for the aerodynamic windows since the pressures produced by them must be controlled to within 1%. Likewise, precision control systems must be provided for the mechanical valves, since, in the open position, the valve bores and the launch tube bore must be aligned to within ~0.01 cm.

IV. Design of New End Closure

Here, a brief preliminary design of the aerowindow end closure is carried out to determine what mass flows and reservoir pressures, sizes, and masses would be required. The aerowindow is sketched in Fig. 1. The numbers in the figure denote the state points or stations for analysis of window operation. The drive gas enters from a plenum at state 1 through an annular nozzle traversing states 2 and 3. The drive gas comes to near stagnation at state 4. Some of the gas reverses and is assumed to be choked at state point 6. The pressure at state point 6 will be estimated to be some fraction of that at state point 4, based on experimental ejector data. The operating conditions of the aerowindow can then be found by applying the continuity and energy equations between states 2, 6, and 5; the momentum equation between states 3, 6, and 4; and the choking condition at states 6, 5, and 2.

We consider the design of an aerowindow end closure system for the space launch system of Ref. 9. The ram accelerator tube fill pressure in this case is 50 atm, which will be p_{30} in our design. About 90% of the ram accelerator tube length in the design of Ref. 9 is for operation above the detonation velocity, and the given tube diameter is 0.85 m. We will design for this diameter. We consider the supply gas for the aerowindow to be air at 300 K. For our design, we select $\theta = 10$ deg, $M_1 = 2.0$, and $A_2/A_6 = 0.3$. (A denotes the flow area at any station in Fig. 1.) In the work of Ref. 19, for supersonic primary flow ejector pumps, pressure ratios up to ~6 were achieved. Based on these results, we will assume that $p_6 = 0.2 \times p_4$. Following the analysis outlined above, we can readily calculate that the plenum pressure for the drive nozzle will be 72.9 atm and the required mass flow for one window is 2.94×10^6 g/s.

One method to supply the window drive air is to have the airflow from a previously pressurized reservoir through a variable area throat to the plenum for the window drive nozzles. The variable area throat could be a throat equipped with a moveable, tapering pintle. As the pressure in the reservoir dropped, the throat could be opened up to maintain the pressure in the window drive nozzle plenum constant. We assume that the initial pressure in the reservoir is twice the required plenum pressure (i.e., 146 atm), and that the maximum window operating time will be 20 s. The reservoirs are assumed to be initially full of air at 300 K. Allowing for isentropic expansion of the air in the reservoirs, the required reservoir volume can be calculated to be 916 m^3. This could be accommodated in a cylinder of 0.85-m i.d., 1610 m long, or in a sphere of 12.0-m i.d.

Assuming the pressure vessels to be made of a V-modified 4330 steel, taking a safety factor of 3, and using standard design methods, we can calculate the mass of two cylindrical vessels to be 956 metric tons, and that of two spherical vessels to be 705 metric tons. These reservoir vessels are large and massive, but need to be compared with the corresponding ram accelerator launch tube to see if they represent a significant additional incremental mass and cost on a percentage basis. In the space launch system of Ref. 9, for a muzzle velocity of 9 km/s, the launch tube is 3.15 km long. For simplicity, we assume the entire tube to have the dimensions given in Ref. 9 for operation above the detonation velocity—i.d. of 0.85 m and wall thickness of 0.50 m. Assuming the tube to be made of steel, its mass would be 52,100 metric tons. Thus, the total mass of the air storage vessels required for the aerowindow tube end closures is 1–2% of the mass of the main launch tube. Hence, their construction should add only a correspondingly modest cost increment to the launch system.

A second method of operating the aerowindows would be to take liquid nitrogen (LN_2) from a storage vessel, pump it up to the window plenum pressure and mix it with the output from a rocket engine combustor to provide the required source of 300 K high-pressure gas. For example, a Space Shuttle Main Engine (SSME) combustor has a plenum pressure of 204 atm,[20] which considerably exceeds that of the window plenum and could be used for this application. For a 20-s run of the aerowindow discussed above, 72.7 m^3 of LN_2 would be required, which could be stored in a sphere of 5.18-m i.d. This storage vessel is considerably smaller than that required for the compressed-air-driven window and, also, needs to operate only at low pressures. The total heat required to boil LN_2 and heat the gas to 300 K is 432 J/g. Thus, the heat release required to process the window mass flow of 2.94×10^6 g/s is 1.27×10^9 W. Conservatively taking the combustion efficiency of the SSME combustor as 0.50, it can be estimated to release 2.99×10^9 W of thermal power. Thus, one SSME combustor could easily provide the thermal power to operate the aerowindow in question. This mode of operation might well allow easier modulation of the window pressure, by varying the engine propellant and LN_2 flow rates. Also, the window operating time could be extended perhaps more easily by increasing the size of the low-pressure LN_2 storage vessel and rocket engine combustor propellant storage.

V. Summary and Conclusions

The ram accelerator is a chemically driven ramjet-in-tube device which has been demonstrated experimentally over the velocity range 0.7–2.5 km/s and has the potential for operation up to 10 km/s. It could be used for direct launch into space or for large ballistic ranges. The ends of the main ram accelerator tube must have closures which support substantial pressure differences. If diaphragms pierced by the projectile are used as closures, there is a risk of damage to the projectile or tube on projectile-diaphragm impact and a risk of jamming the inlet diaphragm between the projectile and tube. The end closures could also be removed prior to projectile arrival—this could involve explosively removed closures or fast acting mechanical valves. Such closures must be activated after the projectile is already under way; hence, should the closures fail to properly clear the tube, there is potential for catastrophic damage to the projectile and tube.

A new end closure concept was presented which avoids these difficulties. It is the use of a axial flow aerodynamic window which uses the momentum of a axial air jet to support the necessary pressure difference without there being any solid object in the tube bore at the closures. The aerodynamic window is used in tandem with a moderately fast mechanical valve to limit the operating time of the window and the air supply required. However, the aerodynamic window system avoids the problems of the other end closures described above at the cost of an increase in system complexity. A brief design of the aerodynamic window system was carried out, and the pressures, flow rates, and stored gas requirements were estimated. Designs driven by stored compressed air or by a rocket engine combustor were considered. The stored compressed air aerodynamic window system proposed has only 1–2% of the mass of the main launch tube, and therefore, should add only a proportionately modest increase in cost to the overall launch system. If the difficulties mentioned above with the solid end closure systems prove to be significant, the aerodynamic window end closure system may offer a solution at the cost of some increase in system complexity.

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