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Operation of Quasi-Two-Dimensional Projectiles in a Ram Accelerator

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Introduction

THE ram accelerator is a novel launcher concept that accelerates a supersonic projectile in a tube filled with combustible gas.[1,2] Shock waves around the projectile ignite the gas, and combustion supports a high-pressure region on the base of the projectile. Several propulsive modes have been proposed and investigated experimentally, theoretically, and numerically. Most experimental work to date has been done on the thermally choked mode, where the projectile is below the Chapman–Jouguet (CJ) detonation speed of the mixture.[3]

In prior experiments, most projectiles were designed with a nose cone attached to a truncated conical base. Figure 1 shows a typical projectile used in the University of Washington (UW) ram accelerator facility. The fins are required to center the projectile as it travels down the tube. Other ram accelerator facilities have used rails on the tube wall to guide an axisymmetric projectile.[4] The fins and rails obscure the flowfield around the projectile, making optical and spectroscopic diagnostics difficult. Visualization techniques are further complicated by the curved tube wall.

A two-dimensional ram accelerator without fins or rails obstructing the flow over the projectile would greatly assist investigation of the complex flowfield, as well as simplify the geometry for computational modeling. This has motivated the construction of a two-dimensional ram accelerator with a rectangular bore at Hiroshima University (HU) in Japan.[5] The projectile and tube cross section of this facility are shown in Fig. 1 (not to scale). Lacking fins, the projectile is guided by rails on the tube wall, allowing pure two-dimensional flow over the projectile. Windows on the tube side walls provide convenient access for flow visualization.

The feasibility of ram acceleration in a two-dimensional geometry is the subject of this Note. A quasi-two-dimensional (Q2D) projectile was designed that can be used in a conventional ram accelerator with a circular cross section (Fig. 1). This paper reports the results of experiments using this Q2D projectile in the UW ram accelerator.

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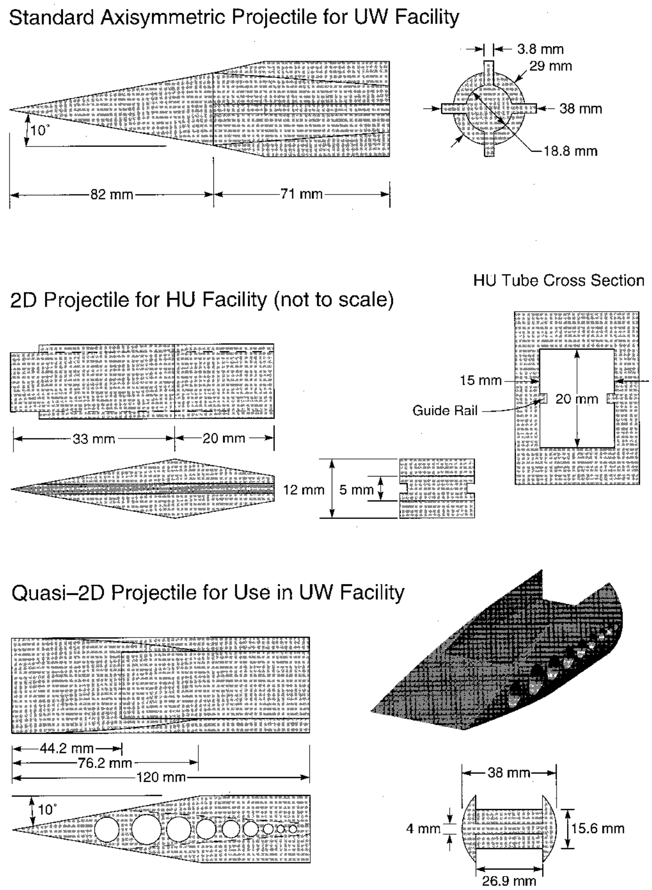

Fig. 1 Axisymmetric projectile for use in the UW facility, two-dimensional projectile for use in the HU facility, and Q2D projectile for use in the UW facility.

Experimental Facility and Procedure

The facility used in these experiments is the 38-mm bore, 16-m-long ram accelerator at the UW. A helium gas gun launches the projectile into the test section at supersonic velocity. The combustible gas mixture is contained in the test section by diaphragms at each end. Electromagnetic sensors, for tracking a magnet carried onboard the projectile, and pressure transducers, for monitoring wave activity at the tube wall, are mounted at 40-cm intervals along the test section.

The Q2D projectile shown in Fig. 1 was fabricated from aluminum alloy. The throat to tube area ratio is 0.4. Holes through the projectile are used to reduce the mass to 87.6 g. The curved extensions on the rear half of the projectile contact half the circumference of the tube and act to stabilize the projectile. The projectile was launched from the helium gas gun with a conventional perforated polycarbonate obturator.[6] The obturator required reinforcement with a 1.7-mm perforated aluminum alloy face plate to prevent it from breaking on the base of the Q2D projectile when accelerated by the gas gun.

Experimental Results and Discussions

Diffuser Starting in Inert Gas

As a preliminary experiment, the Q2D projectile shown in Fig. 1 was fired into the test section filled with pure nitrogen at 25 atm to evaluate the diffuser performance. The result is shown in Fig. 2. The entrance velocity was 1180 m/s, equivalent to a Mach number of $M = 3.3$ in nitrogen. The diffuser properly started, meaning supersonic flow was established past the projectile throat. Because of friction and aerodynamic drag, the projectile gradually decelerated in the first 8 m of the test section. At this point, when the projectile velocity had decreased to 910 m/s ($M = 2.6$), the flow around the projectile

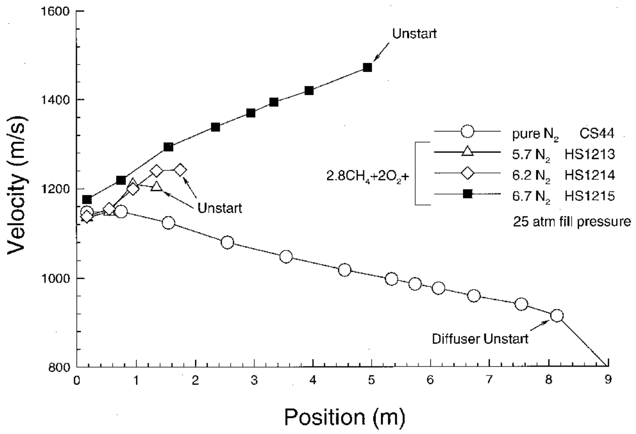

Fig. 2 Projectile velocities as a function of distance traveled in the ram accelerator test section.

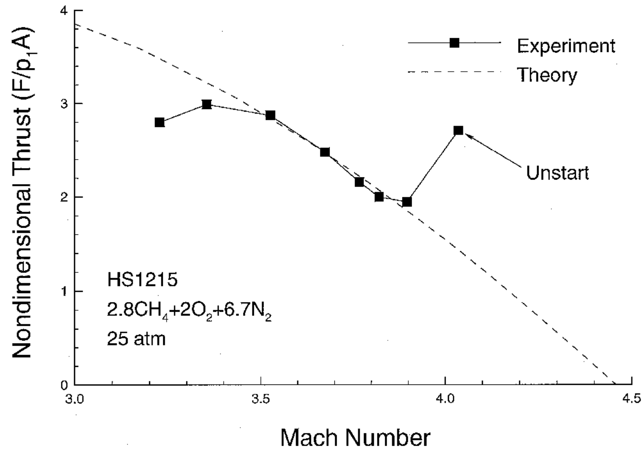

Fig. 3 Nondimensional thrust as a function of projectile Mach number for Q2D projectile and for thermally choked theory. F = thrust, p_1 = fill pressure, and A = tube cross-sectional area.

choked at the throat, generating a normal shock wave in front of the projectile and unstarting the diffuser. Greater aerodynamic drag caused by the normal shock in front of the projectile caused an increased deceleration (Fig. 2). This result indicates that the projectile must be injected into combustible gas at a Mach number greater than 2.6 when ram acceleration is attempted. This Mach number is slightly greater than the ideal isentropic starting Mach number of 2.4 because of the losses across the oblique shock waves.

Ram Acceleration in Combustible Gas

After the diffuser was successfully started in inert gas, Q2D projectiles were fired into methane-based combustible mixtures at 25-atm initial pressure. The methane and oxygen molar values were fixed at $2.8CH_4 + 2O_2$, and the amount of nitrogen diluent was varied to find the operational range. This mixture class was chosen because $2.8CH_4 + 2O_2 + 5.7N_2$ has proven to be a reliable mixture to initiate ram accelerator operation in the UW facility, and has formed the basis for mixtures in most other ram accelerators. Figure 2 shows velocity–distance histories for several Q2D shots. In the $5.7N_2$ mixture, the driving combustion wave surged past the projectile throat, causing an unstart, after the projectile traveled 1 m into the test section. Increasing the dilution to $6.2N_2$ increased the distance the projectile traveled before unstarting to 1.5 m. The nearly immediate unstarts suggest that these mixtures are too energetic for the Q2D projectile, and so more nitrogen was added to reduce the mixture energy content.

When a projectile was fired into a $6.7N_2$ mixture, it drove 6 m into the ram accelerator section before unstarting. With the entrance and unstart velocities of 1180 and 1530 m/s, respectively, the projectile's velocity was increased by 350 m/s, yielding an average acceleration of 8100 *g*. Since this mixture has a CJ detonation velocity of 1620 m/s, the projectile accelerated to more than 90% of the CJ velocity before unstart. Because the projectile unstarted after several meters of travel in the ram accelerator section, it is difficult to determine whether the unstart was the result of combustion and gasdynamic phenomena or whether it was caused by a structural failure of the projectile.

The nondimensional thrust on the projectile (defined as thrust normalized by fill pressure and tube area) for the successful experiment with $6.7N_2$ is plotted as a function of Mach number in Fig. 3. The thrust was measured by fitting a fourth-order polynomial to the first-order finite difference of the position–time history of the projectile and then differentiating to find acceleration. Also shown in Fig. 3, as a dashed line, is the theoretical thrust as predicted by an equilibrium code for the thermally choked model of ram accelerator operation. Note that the theoretical thrust goes to zero at the CJ Mach number of 4.47. The agreement is seen to be quite good, until the projectile reaches Mach 4, where an increase in thrust is observed. This increase is also observed with conventional, axisymmetric projectiles and is termed transdetonative operation, since it allows the projectile to exceed the CJ speed of a given mixture.[2] In this experiment, the projectile unstarted before it reached the CJ speed. The fact that the observed projectile acceleration agrees well with thermally choked theory reinforces a major tenet of that theory: thrust is independent of the projectile's geometry.[1,7]

In the $2.8CH_4 + 2O_2 + XN_2$ class of mixture, the operation of a conventional, axisymmetric projectile in the UW ram accelerator is usually initiated with $5.7N_2$. The Q2D projectile was unable to sustain ram acceleration in this mixture, and the dilution had to be increased to $6.7N_2$. Several possible explanations exist as to why the Q2D requires a more dilute mixture to operate. A two-dimensional oblique shock is stronger than a conical shock at a given Mach number. The greater temperature rise associated with this shock may promote combustion to occur earlier on the projectile body. Also, the stronger shock results in a lower diffuser efficiency, which according to a one-dimensional model of the thermally choked ram accelerator, has the effect of moving the normal shock closer to the projectile throat and increasing the potential for an unstart. Thus, while the observed acceleration in a successful experiment is independent of geometry, the range of mixtures that will support ram acceleration is not.

Conclusions

Although this work is only a preliminary investigation of ram acceleration with a two-dimensional geometry, it has produced two important results. First, ram acceleration is possible with a two-dimensional, wedge-shaped projectile. Second, the observed accelerations agree well with the thermally choked theory, providing further evidence that thermally choked performance is independent of projectile geometry. This work also forms a link between the two-dimensional ram accelerator facility at HU in Japan and other ram accelerator facilities.

Acknowledgments

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Further Examination of Enthalpy Rocket Performance

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Introduction

PARKER and Humble[1] examined the potential performance of enthalpy rocket propulsion, based on the transfer of stored thermal energy from an inert metal or ceramic capacitor into a nonreacting working fluid; Gany[2] also examined this concept. In these analyses, the thermal capacitor material was assumed to begin as a liquid at its melting point and end as a solid, also at the melting point. In addition, the total mass of the system was assumed to consist of the capacitor and working fluid masses, with no additional inerts or payload other than the capacitor itself. Parker and Humble[1] took a somewhat convoluted approach to arriving at their final expression for velocity increment ΔV, which can easily be shown to reduce to the standard velocity increment equation

$$\Delta V = I_{sp} g_c \, \ell n[(m_{cap} + m_{WF})/m_{cap}] \qquad (1)$$

where I_{sp} is the specific impulse of the working fluid at the melting temperature of the capacitor material, m_{cap} is the mass of the thermal capacitor, and m_{WF} is the total mass of the working fluid, with the two masses being related by the heat required to raise the working fluid from its initial temperature (not defined in Ref. 1) to the capacitor melting temperature. Gany[2] recognized the equivalence of Eq. (1) for this analysis and used it to derive a velocity increment equation utilizing idealized equations for the working fluid expansion process and setting the total latent energy storage of the capacitor equal to the heat required to raise the working fluid to the capacitor melting temperature by means of Eq. (3) of Ref. 2: $m_{cap}\Delta Q_{melt} = m_{WF} c_p T_{melt}$. Implicit in the previously mentioned Eq. (3) is the assumption that the working fluid is initially at absolute zero temperature and that there are no latent heats associated with heating this fluid from absolute zero to the capacitor melt temperature.

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In the analysis presented here, whose main contribution will be to examine the effects of using the thermal capacitor more completely by allowing it to start at temperatures well above its melting point and end at temperatures well below it, and the effects of different means of staging working fluid flow through the capacitor, most of the results will assume initial working fluid conditions as gas at 273 K; a brief examination of more realistic initial conditions is presented at the end of this note. Equation (1) was used as the starting point in this analysis, with the specific impulse of the working fluid (for infinite expansion ratio and a zero-back-pressure environment) being calculated from

$$I_{sp} = (2c_p T_0/g)^{1/2} = [2\gamma R/g(\gamma - 1)]^{1/2}(T_0/MW)^{1/2} \qquad (2)$$

where $\gamma = 1.4$ for a diatomic working gas and 1.667 for a monoatomic gas, T_0 is the working fluid total temperature after heat exchange with the capacitor, and MW is the molecular weight of the working fluid. The relationship between working fluid and capacitor masses is obtained by equating the latent heat stored in the capacitor to the heat required to raise the working fluid from its initial temperature to the capacitor melting point, resulting in

$$m_{WF} = [\Delta Q_{melt}/c_p(T_{melt} - T_{init})]m_{cap} \qquad (3)$$

$$\Delta V = I_{sp} g_c \, \ell n[1 + \Delta Q_{melt}/c_p(T_{melt} - T_{init})] \qquad (4)$$

Velocity increment values calculated by Parker and Humble,[1] Gany,[2] and by the use of Eqs. (2–4) are presented for several combinations of working fluid and thermal capacitor material for the scenario where only fusion heat is extracted from the capacitor in Table 1. There are significant differences in absolute values calculated, resulting from the different initial conditions assumed for the working fluid. Because of the nonlinear interactions between various working fluid and capacitor properties, these differences do not show up as constant ratios; the differences are particularly pronounced for the lithium capacitor because its low melting temperature makes it particularly sensitive to different initial working fluid temperature assumptions through the $(T_{melt} - T_{init})$ term in Eqs. (3) and (4). (Note that working fluid initial conditions are not specified by Parker and Humble[1]; part of the differences appearing in Table 1 may result from their using conditions other than gas at 273 K.)

As indicated, one purpose of this study was to evaluate additional velocity increment potential associated with using specific heat storage as well as the latent heat storage capacity of the capacitor materials; relevant properties for several attractive candidates are presented in Table 2. (The peak operating temperatures listed in Table 2 are somewhat arbitrary, being chosen to be sufficiently lower than the boiling points to minimize carrier vaporization problems.) It is particularly instructive to compare columns 5, 7, and 8 of Table 2. Column 5 gives the latent heat available per gram of material, column 7 gives the total heat storage between the peak temperature and the solidus end of the melting point, and column 8 gives the total heat storage between the peak temperature and 500 K; the total storage capability is much larger than the latent heat storage capacity, suggesting further examination of the enthalpy rocket concept using some or all of this additional capacity.

The procedure used to examine this potential is outlined next; in this phase of the study, it was assumed that all working fluid passes through the entire capacitor bed, with the isothermal bed temperature decreasing with time. First, a basis weight of capacitor material was chosen. A small temperature decrement from the initial peak temperature was selected and the amount of working fluid mass passing through the capacitor associated with this decrement was calculated as

$$m_{WF,j} = (\text{Basis Wt})c_{p,cap}\Delta T_j/c_{p,WF}(T_{av,j} - 273) \qquad (5)$$