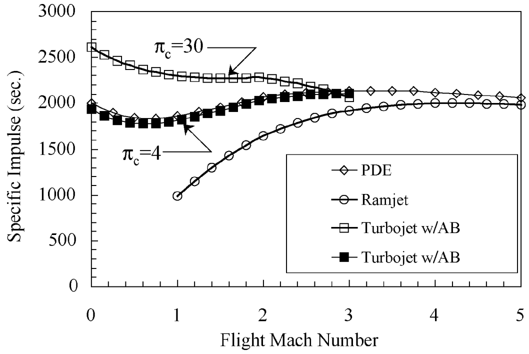

Fig. 3 Specific impulse as a function of Mach number for PDE, ramjet, and turbojet with afterburner. For all systems $\gamma = 1.3$, inlet and nozzle are ideal, and the nozzle inlet temperature is 4200 R (2300 K). For the turbojet, adiabatic compressor and turbine efficiencies are 0.85 and 0.90, respectively. The turbine inlet temperature is 3000 R (1670 K). The fuel heating value is 19,000 BTU/lb_m (44,000 kJ/kg).

to calculate the specific thrust and specific impulse over the Mach-number regime. The specific impulse results are shown in Fig. 3. A Mach-number dependent static inlet temperature profile was used for these calculations in order to account for altitude effects.[7] The nozzle inlet total temperature was chosen to be 4200 R (2300 K). The ratio of specific heats was 1.3. The fuel heating value was 19,000 BTU/lbm (44,000 kJ/kg), typical for many hydrocarbon fuels.

Also shown in the Fig. 3 are the performance results for a ramjet and for afterburning turbojets with compressor pressure ratios of 30 and 4. For the turbojet calculations the compressor and turbine adiabatic efficiencies were again 0.85 and 0.90, respectively. The combustor and afterburner were assumed loss free (i.e., constant total pressure). The turbine inlet temperature was 3000 R (1670 K). It can be seen that the ideal PDE performance is fairly consistent over the Mach-number regime and that it is comparable with a non-ideal, afterburning turbojet having a compressor pressure ratio of 4.0. For turbojets of a more realistic pressure ratio, the PDE shows significantly less specific impulse and (not shown) specific thrust. Compared with the ramjet, the performance advantages of a PDE are clear at Mach numbers below 3.0. Beyond this, there does not appear to be significant benefit. These PDE performance results are smaller than what is typically listed in the literature[1,2,10]; however, because they represent computed results from a validated code, it can be argued that they are more representative of an idealization in the sense of being as good as can be expected.

Other PDE applications can be examined in a straightforward manner using the map of Fig. 1. Examples would include gas-turbine topping cycles, afterburners (bypass duct or full flow), even ejector-based cycles (if some assumptions are made regarding the work transfer process).

Of the applications that have been examined, the process has been made easier through the use of Eq. (9); however, it should be kept in mind that for a given application, not all values of q_0 (and therefore enthalpy ratio) are possible. Also, the results shown represent a particular gasdynamic cycle. Other cycles, such as PDE cycles with valved exhaust (or low-loss, variable backpressure systems), or those employing shaped tubes can lead to different and possibly superior performance to that presented.[11,12]

Conclusions

It has been demonstrated in this work that idealized airbreathing PDE performance can be mapped onto a single plot of total pressure ratio vs total enthalpy ratio. It has further been shown that this format is useful in system studies because the PDE can be viewed as simply another component with straightforward input and output. The idealized PDE performance data were obtained from a one-dimensional CFD code, and it has been shown that this is a more realistic approach than purely analytical methods. The performance shown is generally below that which has been previously reported for so-called idealized PDE performance but is still idealistic in that the losses captured are only those endemic to the cycle. A similar map that incorporates losses such as those caused by heat transfer, viscous effects, and valving could easily be generated.

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Impulse Correlation for Partially Filled Detonation Tubes

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Introduction

THE effect of nozzles on the impulse obtained from a detonation tube of circular cross section has been the focus of many experimental and numerical studies. In these cases, the simplified detonation tube is closed at one end (forming the thrust surface) and open at the other end, enabling the attachment of an extension. A flowfield analysis of a detonation tube with an extension requires considering unsteady wave interactions making analytical

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and accurate numerical predictions difficult (especially in complicated extension geometries). To predict the impulse obtained from a detonation tube with an extension (considered a partially filled detonation tube), we utilize data from other researchers to generate a partial-fill correlation.

Several experimental and numerical researchers have examined how the single-cycle impulse is affected by an extension. In these experimental studies, the tube is filled with the initial explosive mixture while the added extension is filled with an inert gas, usually atmospheric air. A thin diaphragm is used to separate the two mixtures. Zitoun and Desbordes[1] measured the impulse by integrating the thrust surface pressure differential of ethylene–oxygen mixtures at standard conditions in a tube with extensions having the same circular cross section. Zhdan et al.[2] directly measured the impulse using a ballistic pendulum arrangement of acetylene–oxygen mixtures at standard conditions in a tube with extensions having the same circular cross section. Similarly, Cooper et al.[3] and Falempin et al.[4] used a ballistic pendulum to measure impulse values of ethylene–oxygen mixtures in detonation tubes with attached extensions having a constant circular cross section and also in extensions of varying dimensions. Li and Kailasanath[5] numerically studied the effect of varying the length filled with the explosive mixture in tubes of constant cross-sectional area on the impulse. They applied an exponential curve fit to their data relating the fuel-based specific impulse to the amount of the tube length filled with the explosive mixture.

These researchers either kept the tube length filled with the explosive mixture constant and added extensions of varying length or they kept the total tube plus extension length constant while varying the tube length filled with the combustible mixture. To obtain a quantitative measure of comparison between the different facilities, we calculate the fill fraction of the combined tube and extension assembly given the published dimensions. This work is to extend previous modeling work on detonation tubes[6] to the case of partial filling and show how simple analytical estimates can be obtained for the impulse in both the fully and partially filled cases.

Data for Partially Filled Tubes

The data is plotted as a function of the fractional tube volume filled with the explosive mixture (Fig. 1). The single-cycle impulse I was normalized by the impulse I^0 for a fully filled tube. The predictions of our single-cycle impulse model[6] for a fully filled tube were used to normalize the experimental data of Zitoun and Desbordes[1] because experimental data of I^0 were not available.

Because a diaphragm of finite mass is used to separate the initial explosive mixture from the inert mixture of the extension in the experimental tests, incremental impulse is imparted to the tube due to the additional tamping mass of the diaphragm. For small tubes, even very thin diaphragms can equal a significant fraction of the initial explosive mixture mass, increasing the tamping effectiveness.[7] Based on information of the diaphragms provided by the researchers,[1,2,4,8] we use the Gurney model (see Ref. 7) to correct the measured impulse values for the diaphragm effect as described by Cooper and Shepherd.[8] Briefly, the Gurney model assumes a linear velocity gradient in the expanding product gases that are sandwiched between the driven mass (the detonation tube) and the tamper mass (the diaphragm). The final velocity of the driven mass is determined from the conservation equations and depends on the available chemical energy of the explosive. The impulse corrections applied, measured as a percentage of the measured impulse, are less than 2.3% for Cooper et al.,[3] less than 21.3% for Falempin et al.,[4] less than 22.3% for Zhdan et al.,[2] and less than 25.1% for Zitoun and Desbordes.[1] Figure 1 contains the corrected experimental data.

Partial-Fill Correlation

For the range of experimentally tested fill fractions ($0.15 < V/V^0 < 1$), a linear relationship exists between the impulse fraction and the fill fraction

$$I/I^0 = 0.814(V/V^0) + 0.186 \tag{1}$$

The numerical simulations by Li and Kailasanath[5] were used to determine the behavior of the partial-fill correlation at fill fractions close to zero ($V/V^0 < 0.15$). They found that the impulse behavior near the origin in Fig. 1 can be approximated as

$$I/I^0 = 3.560(V/V^0) \tag{2}$$

The intersection of these two linear relations [Eqs. (1) and (2)] occurs at a fill fraction of 0.0676, which determines the range of applicability for each equation.

As shown in Fig. 1, the maximum impulse from a detonation tube is obtained by completely filling it with the explosive mixture. In other words, filling only a fraction of the tube volume with the explosive mixture results in obtaining only a fraction of the maximum possible impulse. Equations (1) and (2), written in terms of impulse, can be rewritten as mixture specific impulse $I_{sp} = I/g\rho_1 V$ normalized by the specific impulse I_{sp}^0 of the fully filled tube. The initial explosive mixture density is represented by ρ_1 and g is the standard gravitational acceleration. For $0.0676 < V/V^0 < 1$,

$$I_{sp}/I_{sp}^0 = 0.814 + 0.186(V^0/V) \tag{3}$$

and for $0 < V/V^0 < 0.0676$,

$$I_{sp}\big/I_{sp}^0 = 3.560 \tag{4}$$

The data of Fig. 1 are replotted in terms of specific impulse in Fig. 2. The specific impulse is found to increase as the explosive mixture mass decreases, which indicates a specific performance increase even though the total impulse decreases. In the limit as the explosive

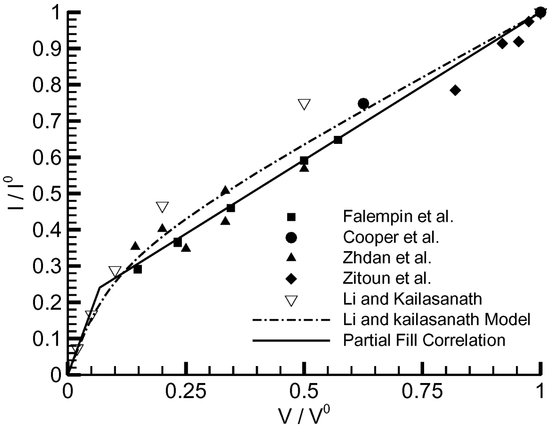

Fig. 1 Normalized impulse I/I^0 from published data[1−5] vs fill fraction V/V^0 for tubes with constant circular cross section and comparison to partial-fill correlation.

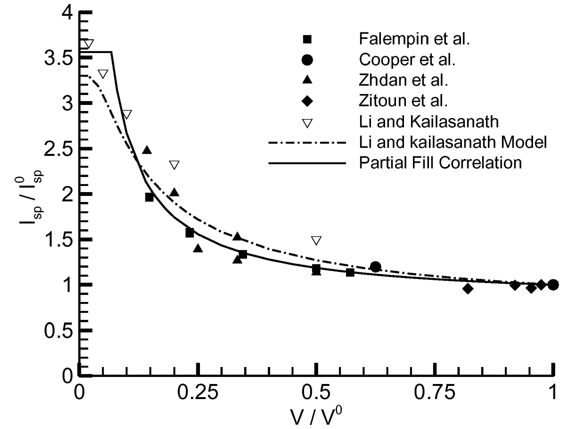

Fig. 2 Partial-fill correlation in terms of normalized specific impulse I_{sp}/I_{sp}^0 with published data[1−5] vs fill fraction V/V^0 for tubes with constant circular cross section.

mass tends to zero, the specific impulse ratio tends to a constant value.

The crucial issue in understanding how the impulse behaves as a function of the fill fraction is to consider the relative masses of the detonation tube, combustible mixture, and the inert gases. Because the combustible mixture has a constant amount of stored chemical energy per unit mass, it is the distribution of this chemical energy into accelerating the tube, product gases, and inert gases that determines the impulse imparted to the tube. When energy and momentum conservation are considered, the impulse imparted to the tube must equal the impulse imparted to the expanding detonation products and the inert gases. Thus, for a constant combustible mixture mass, increasing the mass of inert gas decreases the exit velocity of the gases. This results in more of the stored chemical energy to be imparted to the tube, causing an increase in the specific impulse as shown in Fig. 2. In the limit of infinite inert gas mass (or zero combustible mixture mass), the average gas exit velocity goes to zero and the maximum amount of stored chemical energy goes into driving the tube. This situation corresponds to a tube of infinite length, where the specific impulse reaches a limiting value.

The impulse curve of Fig. 1 is based on the total mass of the combustible mixture and the inert gases contained in the tube. The mass of the combustible mixture and inert gases depend on their initial density and fill fraction. For the experimental data discussed earlier, the densities of the combustible mixture (ethylene–oxygen or acetylene–oxygen) and inert gas (atmospheric air) are approximately equal. This means that the total mass within a tube of constant length remains approximately constant regardless of fill fraction. When the amount of combustible mixture in the tube is decreased, a corresponding decrease in the available stored energy within the tube occurs. As a result, decreasing the fill fraction decreases the impulse imparted to the tube such that a fully filled tube produces the maximum impulse because the available stored chemical energy is maximized, whereas a tube containing only inert gases ($V/V^0 = 0$) produces zero impulse because the available chemical energy equals zero.

To summarize, our partial-fill correlation consists of the two relationships, Eqs. (1) and (2) for impulse or, alternatively, Eqs. (3) and (4) for specific impulse. This correlation is empirical in nature and is derived from a limited amount of experimental and numerical data. However, as shown subsequently, it compares very well with multicycle data over a wide range of fill fractions. Its advantages are that it is simple, and in conjunction with our previous models of fully filled tubes, provides a rapid means of estimating the ideal impulse of partially filled detonation tubes.

Comparisons with Partial-Fill Correlation

Our partial-fill correlation, Eq. (3) for $0.0676 < V/V^0 < 1$ and Eq. (4) for $0 < V/V^0 < 0.0676$, is compared to multicycle experiments by Schauer et al.[9] in hydrogen–air mixtures (Fig. 3). Data were obtained for a variety of tube dimensions, fill fractions, and cycle frequencies. Impulse and thrust measurements were taken with a damped thrust stand, and for our correlation, we assume that multicycle operation is equivalent to a series of ideal single cycles. These data were not considered in the development of the partial-fill correlation, which enable an independent test to the experimental data for validation purposes.

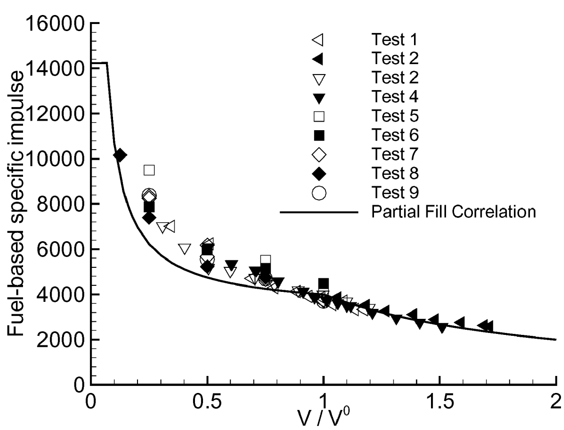

Fig. 3 Comparisons of fuel-based specific impulse for the partial-fill correlation and multicycle experimental data[9] as a function of fill fraction V/V^0.

The fill fractions in Fig. 3 greater than one correspond to overfilling the detonation tube, and in this case, the specific impulse is reduced because only the mixture within the tube contributes to the impulse. The impulse I of an overfilled tube is equal to the impulse I^0 of a fully filled tube. This can be simply accounted for by computing the specific impulse as

$$I_{sp}\big/I_{sp}^0 = (I/\rho_1 g V)\left(\rho_1 g V^0\big/I^0\right) = V^0/V \tag{5}$$

when $V/V^0 > 1$. This relation is precise and valid for all fill fractions greater than one.

Li and Kailasanath[5] proposed a correlation for specific impulse of partially filled tubes based on an exponential curve fit with data from their numerical simulations

$$\frac{I_{spf}}{I_{spf}^0} = a - \frac{(a-1)}{\exp[(L^0/L - 1)/8]} \tag{6}$$

The constant a has values[5] between 3.2 and 3.5.

Equation (6) in terms of fill fractions are compared with our partial-fill correlation (Fig. 1). Both relationships predict zero impulse at a fill fraction of zero as expected. Our partial-fill correlation and the curve fit from the numerical simulations both tend to a constant specific impulse value in the limit of zero explosive mixture.

Conclusions

A simple correlation has been developed to predict the impulse in partially filled detonation tubes. The correlation was based on interpretation of published experimental[1–4] and numerical[5] data. A piecewise linear correlation is found to describe adequately the existing single-cycle and multicycle data for a wide range of fill fractions. The impulse increases with increasing fill fraction, and the maximum value is obtained in a full tube. The specific impulse increases with decreasing fill fraction, and the maximum value is obtained in the limit of vanishing explosive mixture amount. The Gurney model was utilized to correct the experimental data for the impulse increment that is a result of a finite diaphragm mass.

Acknowledgments

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Scramjet Inlet Flow Control Using Combined Magnetohydrodynamics and Glow-Discharge-Plasma Effect

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Introduction

THE realization that conventional aerodynamic control surfaces might not possess sufficient potential to satisfy all of the performance requirements of future hypersonic vehicles has led the aerodynamics community to seek new, unconventional high-speed flow control approaches. The proposed approaches include those applicable to external aerodynamics as well as internal flows in scramjet engines. Broadly, the flow control methods aim to achieve improved 1) external flows leading to increased vehicle aerodynamic performance and 2) internal flows through engines, including scramjet inlets leading to better engine performance particularly under off-design conditions.

Two unconventional methods have recently been proposed to address the goals just listed, both of which employ charged particle action on the gas: glow discharge plasma (GDP)[1–3] and magnetohydrodynamics (MHD).[4–11] The concept of flow control by GDP has been applied primarily to external flows, whereas most of the MHD control research has been directed to the flows in scramjet and ramjet engines.

Glow discharge plasma can be a convenient tool for localized heat addition into the flow. It was proposed to use GDP as a method for heat addition upstream of a shock wave.[2] In other studies, a weakening of bow shocks was observed when heat was added using GDP that formed between the body and the bow shock.[3] The results of these studies demonstrated the potential of the plasma technology in high-speed aerodynamics. The exact nature of plasma-shock-wave interaction is not clearly understood. However, there is broad agreement that the observed phenomena are associated with plasma electrons acquiring energy from the external electric field and transferring it to the gas in interactions with the molecules.[12]

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Previous studies of the application of MHD to engine inlets have shown that the MHD action increases flow compression and mass flow rate.[4,8,9] However, the resulting improvements in flow parameters were incremental. It was also proposed to use MHD to decelerate the flow in front of the combustion chamber of the scramjet engine, with subsequent acceleration of the flow after the chamber.[13] Calculations for a Mach number of $M = 6$ showed that this scheme can increase the scramjet specific impulse. To the best of our knowledge, GDP has not been considered to date for the improvement of scramjet flows.

In this report, we investigate the possibility of enhancing the MHD control of scramjet inlets by simultaneously applying GDP. We present sample results of an analysis, which shows that MHD and GDP can be applied in a complementary fashion to further enhance the benefits that could be gained by applying MHD or GDP alone in the inlet duct. This is because the effectiveness of MHD and GDP vary with the local flow conditions. That is, the local benefit of each action varies from region to region in the inlet flow, and the optimum location for GDP application is, in general, different than that for MHD for a given set of local flow parameters.

MHD and GDP Effects on Flow

Both MHD and GDP flow control mechanisms rely on the relatively small number of charged particles, which are either formed within the gas flow or introduced into it. The ionization level in both cases usually does not exceed 10^{-5}. The actions on the neutrals are caused by the interaction of the charged particles with the external magnetic (in the case of MHD) or the electrical (in the case of GDP) field. The physical mechanisms of these interactions are different. This leads to the fact that the ranges of the flow parameters (velocity, density, local Mach number, etc.) where the GDP and MHD actions are optimal do not necessarily overlap. Therefore, these actions can be complementary rather than competing, and using both MHD and GDP actions in an appropriate sequence can lead to a more significant effect on the flow than that by a single action.

MHD Action

Figure 1 shows a Faraday MHD generator in a channel where the gas flows from left to right. We assume that the gas is made electrically conductive with conductivity of σ. The external magnetic field $\boldsymbol{B}$ is directed normal to the flow, along the z axis as shown. The electric charges (electrons and ions) moving with the flow with velocity u experience an equal but opposite force, which causes the charges to separate. Separation of the charges creates an electric field $\boldsymbol{E}$. When the electrodes on the opposite sides of the flow are not connected, this field is simply $\boldsymbol{E} = -[\boldsymbol{u} \times \boldsymbol{B}]$, which is along the y axis. When the electrodes are linked up through a load resistor R_L, as shown in the figure, the electric field has both x and y components, and the current is induced in the circuit determined by $\boldsymbol{j} + \mu[\boldsymbol{j} \times \boldsymbol{B}] = \sigma \cdot ([\boldsymbol{u} \times \boldsymbol{B}] + \boldsymbol{E})$, where μ is the permeability of the gas. For an ideally segmented Faraday MHD generator, the current has only a y component (as in Fig. 1). The magnitude of the current density is found from $j_y = -\sigma u B(1 - k)$, where $k = E_y/uB$ is the load factor determined by the load resistor R_L (such as $k = 0$ when $R_L = 0$). The magnetic field exerts a Lorentz force $\boldsymbol{F} = [\boldsymbol{j} \times \boldsymbol{B}]$, on the charged particles that acts in the direction opposite to the velocity vector. Thus the magnetic field tends to decelerate flow in the

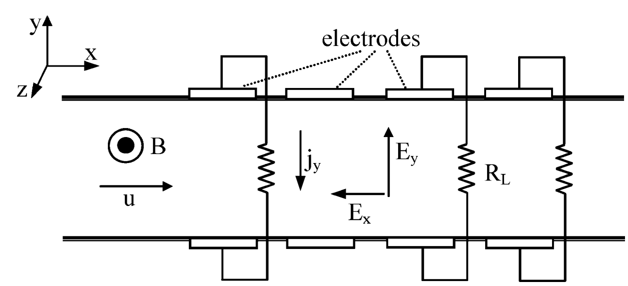

Fig. 1 Segmented electrode Faraday generator.