JOURNAL OF PROPULSION AND POWER
Vol. 26, No. 6, November–December 2010

Technical Notes

Ejector Thrust Augmentation

W. H. Heiser*
U. S. Air Force Academy, USAFA, Colorado 80840

DOI: 10.2514/1.50144

Nomenclature

A	=	throughflow area, ft^2
ff	=	fill fraction of the pulse detonation engine
m	=	mass flow rate, lbm/s
P	=	pressure, lbf/ft^2
V	=	velocity, ft/s
α	=	ratio of primary to secondary flow area at the inlet station
β	=	ratio of diffuser exit area to entrance area
η	=	kinetic energy efficiency
ρ	=	fluid density, lbm/ft^3
ϕ	=	thrust augmentation

Subscripts

a	=	ambient condition, diffuser exit station
e	=	ejector exit station
i	=	ejector inlet station
p	=	primary flow
s	=	secondary flow

I. Introduction

THRUST augmentation is employed to increase the thrust available for propulsion without increasing the energy or power required. The basic mechanism of thrust augmentation is to spread the energy resident in the original flow to additional fluid, the latter usually being taken from the ambient surroundings. Consequently, thrust augmentation is associated with propulsive efficiency as well as thermal efficiency. The original flow is referred to as the primary flow and the additional flow is referred to as the secondary flow. The conventional definition of thrust augmentation is the ratio of the total thrust produced by the primary and secondary flows to the thrust that would have been produced by the isentropic primary mass flow acting alone.

Since the total available exhaust kinetic energy is limited by that resident in the primary flow, thrust augmentation also has it limits. For stationary steady flow devices, such as any ideal incompressible device [1] and the ideal turbofan engine or ideal turbocompressor even with compressible flows [1], it is easily shown that the thrust augmentation cannot exceed

$$\phi = \sqrt{1 + \frac{m_s}{m_p}} \tag{1}$$

The limit given by Eq. (1) requires reversible energy transmission between the primary and secondary flows (e.g., by means of perfect machines). For the two flow turbofan engine, the ratio of the secondary (or fan) flow rate to the primary (or core) flow rate is called the bypass ratio. The thrust specific fuel consumption of any turbofan engine generally decreases with the reciprocal of bypass ratio in accordance with Eq. (1). The ejector is a simple device that can be used to provide thrust augmentation, but the transmission of energy from the primary flow to the secondary flow is accomplished by irreversible mixing, and therefore ejector performance is less than that given by Eq. (1), even with frictionless walls.

Interest in thrust augmentation recurs periodically. For example, steady flow thrust augmentation devices of many types were considered for application by the National Aero-Space Plane program [2], unsteady flow devices are currently being investigated for use by the pulse detonation engine (PDE) [3], and thrust augmentation is certain to play an important role in the future quest for higher propulsive efficiency and lower fuel consumption. The purpose of this Note is to expand the understanding of the behavior of steady and unsteady ejector thrust augmentation devices and, where possible, to identify their limits of performance.

This investigation focuses on stationary or static ejector thrust augmentation for several reasons. To begin, thrust augmentation generally diminishes rapidly with forward speed, simply because it requires more energy from the primary flow to increase the kinetic energy of an already-moving secondary flow [1,4]. Further, most published experimental ejector thrust augmentation data was taken under stationary conditions. Finally, stationary thrust augmentation clearly demonstrates the fundamental principles at work.

II. Steady Flow Ejector Thrust Augmentation

This investigation begins with the analysis of the behavior of the frictionless, stationary, incompressible, ejector–diffuser (referred to hereinafter as the *ejector–diffuser*), as depicted in Fig. 1. The ejector–diffuser connects a diffuser to the exhaust end of a conventional constant-area ejector. The basic function of the diffuser is to reduce the static pressure at the inlet and exit planes of the constant-area section in order to increase the ratio of secondary mass flow rate to primary mass flow rate. The resulting increase in this ratio is expected to increase the thrust augmentation by spreading the available energy among more total flow. The random unsteadiness due to the turbulence that accelerates mixing between the primary and secondary flows is assumed to average to zero on space and time scales much smaller than those of any practical consequence.

The purpose of the ejector–diffuser analysis is to illuminate the influence of the diffuser, which is rather large. This analysis will become especially important for interpreting experimental results, because laboratory thrust augmentation devices often include exhaust diffusers. When $\beta = 1$ the device will be referred to as a *constant-area ejector*. The analysis closely follows that of [1] and, in addition, assumes that the mixing is complete at the entrance to the diffuser and that the flow in the diffuser is isentropic. There is no reason to believe that this is the best possible performance for an ejector–diffuser, because any mixing that occurs within the diffuser is not included. Much more complex analyses are available that include, for example, compressibility, temperature differences, unsteady flows, wall friction, and velocity profiles, but experience has shown that this approach provides a realistic guide to the general behavior of these devices. The assumptions of this analysis are:

1) The primary and secondary fluids and their mixtures have constant density.

2) The primary and secondary flows are isentropic upstream of the inlet station i.

Received 5 April 2010; revision received 2 July 2010; accepted for publication 5 July 2010.

*Professor of Aeronautics, Emeritus. Honorary Fellow AIAA.

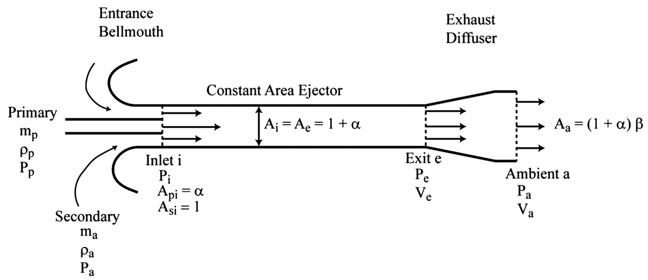

Fig. 1 Schematic diagram of the ejector–diffuser.

3) The static pressure is constant across the inlet station i.

4) The walls of the ejector–diffuser are frictionless.

5) The primary and secondary flows are completely mixed at the exit station e.

6) The static pressure and velocity are constant across the exit station e.

7) The mixed flow is isentropic within the diffuser.

8) The velocities are axial at the inlet i, exit e, and diffuser exit a stations.

9) The static pressure equals atmospheric pressure across the diffuser exit station a.

10) The net thrust equals the total exhaust momentum of the mixed primary and secondary flows.

These assumptions strongly rely upon properly designed, well behaved entrance bellmouth and exhaust diffuser shapes that avoid boundary-layer separation in order to produce attached flow.

The results of this analysis, which is largely based on the conservation of mass and momentum, are

$$\left(\frac{1}{\beta^2}+\alpha^2\right)\left(\frac{\rho_p}{\rho_s}\right)\left(\frac{m_s}{m_p}\right)^2+\left(1+\frac{\rho_p}{\rho_s}\right)\left(1+\frac{1}{\beta^2}\right)\left(\frac{m_s}{m_p}\right) = \frac{2}{\alpha}+\left(1-\frac{1}{\beta^2}\right) \tag{2}$$

and

$$\phi=\left[\left(1+\frac{m_s}{m_p}\right)\left(1+\frac{\rho_p}{\rho_s}\frac{m_s}{m_p}\right)\right]\Big/\left[\beta\left(1+\frac{1}{\alpha}\right) \times\sqrt{1-\frac{\rho_p}{\rho_s}\left(\alpha\frac{m_s}{m_p}\right)^2}\right] \tag{3}$$

It is noteworthy that Eqs. (2) and (3) reduce to the results of [1] when there is no diffuser (i.e., $\beta=1$) and further reduce to Eqs. (1) and (2) of [4] when the primary flow and secondary flow densities are equal (i.e., $\rho_p/\rho_s=1$). Furthermore, it can be seen by inspection that ϕ of the ejector–diffuser is independent of the total pressure of either the primary or secondary flow and, by rewriting Eqs. (2) and (3) in terms of the variable $\sqrt{\rho_p/\rho_s}(m_s/m_p)$, that ϕ primarily depends on α and β when $1/2\le\rho_p/\rho_s\le 2$. The net thrust, of course, does depend on the total pressure of the isentropic primary flow. Finally, it can be seen by inspection of Eq. (2) that either reducing α or increasing β will increase m_s/m_p for any ρ_p/ρ_s. The diffuser therefore increases m_s/m_p as anticipated. Equations (2) and (3) can be combined to show that

$$\text{as } \alpha\to 0,\quad \text{then } \phi\to 2\beta \quad \text{and} \quad \text{as } \alpha\to\infty,\quad \text{then } \phi\to 1 \tag{4}$$

These results also agree with those of [1–6] and confirm the important influence of the diffuser on thrust augmentation. It is especially important to note that, since the static pressure exerted on the internal walls of the exhaust diffuser is below atmospheric, there is a drag on the diffuser. The additional thrust created by the exhaust diffuser is therefore due entirely to the reduced static pressure exerted on the entrance bellmouth caused by the increased secondary flow mass flow and velocity. This is extremely important, since the ejector entrance must be designed to allow the thrust to be generated. A sharp-edged inlet would result in flow separation and high losses. The increased thrust augmentation is ultimately due to spreading the kinetic energy originally resident in the primary flow to the secondary flow.

A valuable result is that the kinetic energy efficiency, defined as the total kinetic energy of the primary and secondary flows divided by the kinetic energy of the isentropic primary flow acting alone, is given by the convenient expression

$$\eta=\left(\frac{\phi}{\sqrt{1+\frac{m_s}{m_p}}}\right)^2 \tag{5}$$

As $\alpha\to 0$. then $\eta\to 0$, and as $\alpha\to\infty$, then $\eta\to 1$, and applying Eqs. (1–5) leads to the conclusion that $\eta\le 1$.

Figure 2 summarizes the quantitative behavior of typical ejector–diffusers according to Eqs. (2), (3), and (5) for $\rho_p/\rho_s=1$. The most important features of Figs. 2a and 2b are that m_s/m_p and ϕ increase rapidly as α decreases and β increases. The significance of these observations is that the thrust augmentation of an ejector–diffuser can greatly exceed that of the constant-area ejector and therefore that α and β must be known in order to properly interpret experimental results. Figure 2c shows that ejector–diffuser η increases as α increases and/or β increases and that η has a wide range of possible variation.

Ejector–diffuser design is a highly developed technology. Reference [5] shows that a compact version employing sophisticated injection of the primary flow (hypermixing nozzles) and diffuser boundary-layer control (end wall energization) has experimentally demonstrated ϕ greater than 2 for α approximately 0.05 and β greater than about 2 (see Figs. 9, 11, and 13 of [5]). Equations (2) and (3) predict ϕ to be approximately 2.5 for these conditions. Furthermore, [5] conclusively confirmed experimentally that ϕ increases steadily as β increases until the exhaust diffuser stalls (see Figs. 8, 9, and 13 of [5]) and that ϕ is independent of the ratio of the total pressure of primary flow to that of the secondary flow. (see Fig. 6 of [5]). The measured ϕ was within 80–90% of the value calculated from Eqs. (2) and (3) over the tested range of $1\le\beta\le 2$ (see Fig. 13 of [5]). Moreover, [4,6] show that properly designed lobed mixer nozzles can be used with extremely short ejectors in order to increase ejector and ejector/diffuser performance. Figure 5 of [6] shows that diffusers on such mixer/ejectors reduce mixing losses and allow mixer/ejector/diffuser thrust augmentation to approach that of the ideal augmentor. Since the diffuser accelerates the secondary flow to a higher velocity, the resulting difference in velocity between the primary and secondary flows at the inlet station is reduced. The lower-velocity difference results in lower mixing losses in the energy transfer process between the two flows. The large-scale low-loss axial vortices set up by primary lobed nozzles results in both rapid ejector mixing and diffuser boundary-layer energization. The results presented in [6] demonstrate that mixer/ejector/diffuser systems can provide a compact jet engine exhaust devices that enhance thrust and reduce noise.

The latter assertions are confirmed by means of the relationship

$$\frac{V_{si}}{V_{pi}}=\alpha\cdot\frac{\rho_p}{\rho_s}\cdot\frac{m_s}{m_p}=\sqrt{\frac{\rho_p}{\rho_s}\cdot\left(\frac{P_a-P_i}{P_p-P_i}\right)}\le 1 \tag{6}$$

which was combined with the ejector–diffuser equations to generate Fig. 3. These results demonstrate that η increases as V_{si}/V_{pi} increases regardless of the value of β. Equation (6) also reveals the important influence of pressures on ejector–diffuser behavior.

III. Unsteady Flow Ejector Thrust Augmentation

A. Quasi-Steady Devices

It was claimed [7] that the energy exchange between the primary and secondary flows could be made highly efficient by means of a quasi-steady process. According to this approach, the primary flow is injected through skewed nozzles in a frictionless rotor that spins transverse to the ejector axis (e.g., Fig. 10-8 of [7] or Fig. 20 of [8]).

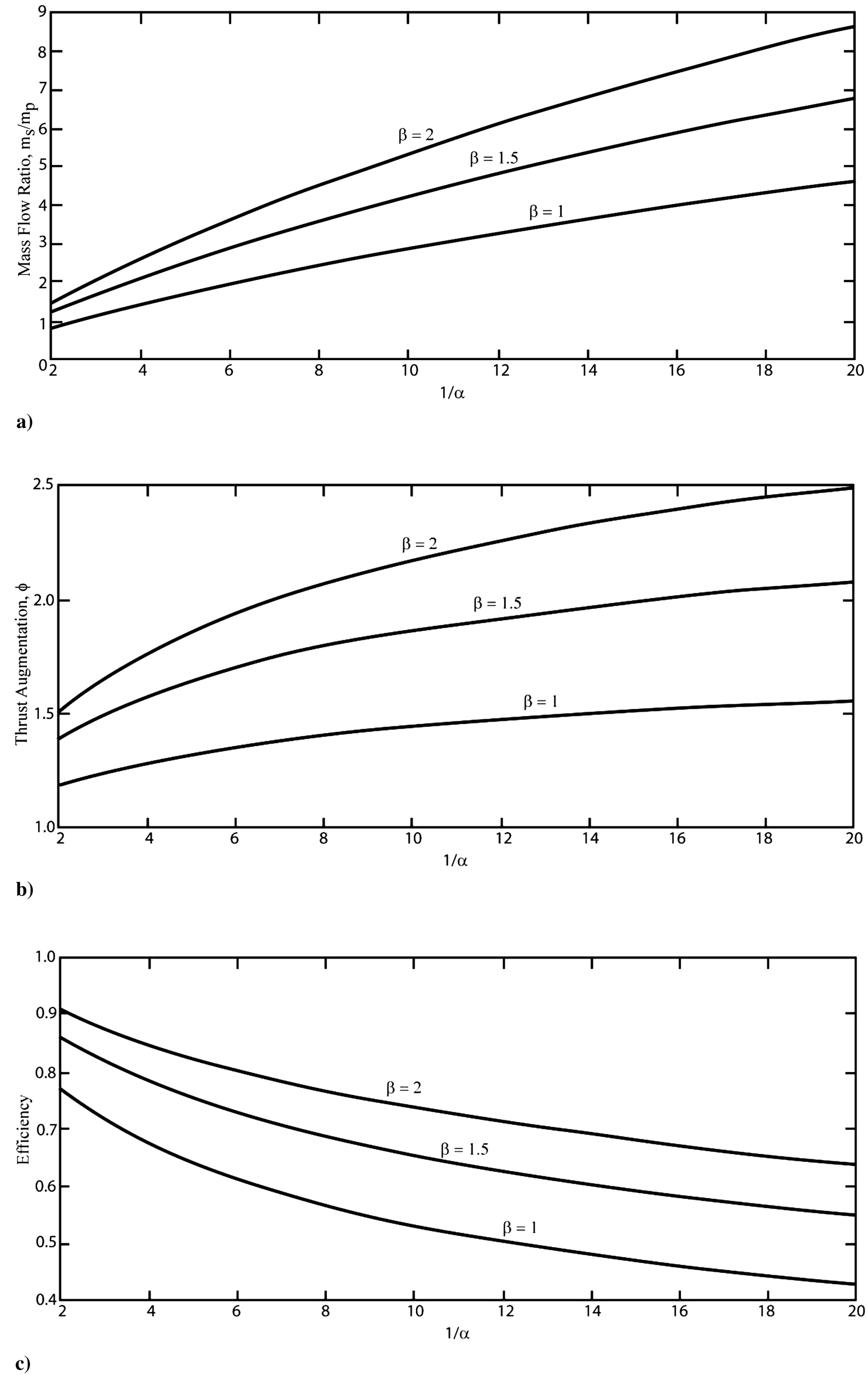

Fig. 2 Plots of a) m_s/m_p vs $1/\alpha$ and β for the ejector–diffuser according to Eq. (2) with $\rho_p/\rho_s = 1$, b) ϕ vs $1/\alpha$ and β for the ejector–diffuser according to Eqs. (2) and (3) with $\rho_p/\rho_s = 1$, and c) η vs $1/\alpha$ and β for the ejector–diffuser according to Eqs. (2), (3), and (5) with $\rho_p/\rho_s = 1$.

The resulting flow appears to be unsteady in the laboratory frame of reference, with the undisturbed primary flow appearing to form a spiral or helix moving down the axis of the ejector. The claim was that the primary flow in the helix was the equivalent of "pseudo blades" that act on the secondary flow in the same way as solid blades in rotating machines. The underlying concept was therefore that the primary flow could exchange energy reversibly with the secondary flow.

Quasi-steady flows can be made to appear steady by moving at the same transverse velocity as the rotating nozzles. Using the configuration and assumptions of the ejector–diffuser, the governing equations in the axial direction in the translating frame of reference are identical to those of the ejector–diffuser described in Sec. II. The transverse motion in the translating frame of reference is easily analyzed, because both the primary and secondary flows have equal transverse velocities. The axial velocity difference between the primary and secondary flows at the inlet station is therefore the same in every translating frame of reference. This observation is equally true for the conventional steady flow ejector, for which it should be noted that the primary and secondary flows also appear to interact at an arbitrary angle depending on the velocity chosen for the translating reference frame. This leads to the conclusion that, no matter how the primary and secondary flows interact within the constant-area control volume, the conservation equations and

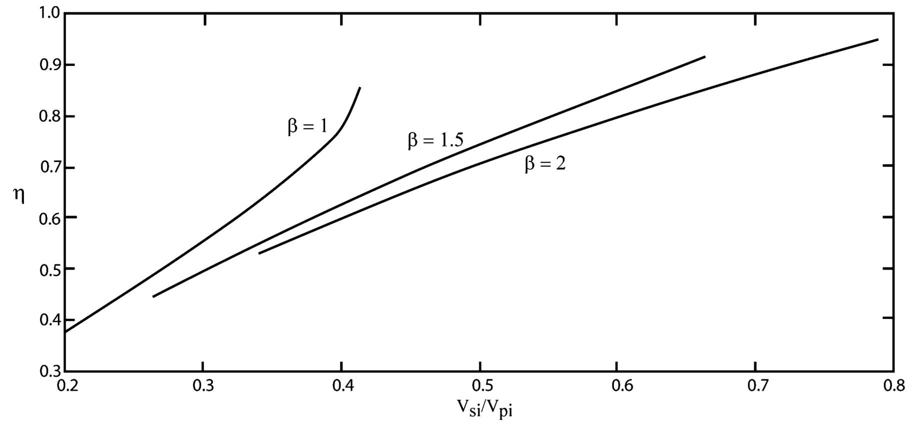

Fig. 3 Plot of η vs V_{si}/V_{pi} and β for the ejector–diffuser according to Eqs. (2), (3), (5), and (6) with $\rho_p/\rho_s = 1$.

boundary conditions are the same and the ultimate performance of these devices must therefore be the same as the ejector–diffuser.

Experimental results for quasi-steady devices [1,8] show that their thrust augmentation behavior is very similar to the ejector–diffuser, as described by Eqs. (2) and (3), which is considerably less than the perfect energy exchange of Eq. (1). Any observed performance improvement over constant-area ejectors could be attributed to enhanced mixing (allowing shorter ducts and less wall friction or improved diffuser behavior), the unspecified exhaust diffuser area ratio (e.g., Figs. 20 and 22 of [8]), and/or experimental uncertainty. Therefore, both theory and experiment lead to the conclusion that designers should expect the behavior of these devices to be the same as that of ejector–diffusers.

B. Unsteady Devices

Unsteady flow devices are those whose flows cannot be transformed into steady flows by means of a translating reference frame. No simple model is available for predicting the thrust augmentation performance of unsteady flow devices. The PDE falls squarely into this category [3]. To improve the performance of the PDE, stationary thrust augmentation produced by an unsteady ejector has been investigated. The preferred configuration has the PDE injecting its exhaust flow into an ejector duct similar to that of Fig. 1 that can entrain air from the surrounding atmosphere [9–14]. The underlying concepts include both the proven advantage of spreading the available PDE exhaust kinetic energy among more mass flow and the possibility of energy exchange between the primary and secondary flows by reversible pressure forces rather than irreversible mixing.

Note should be taken of the fact that when the PDE incorporates a large plenum intended to provide an essentially steady exhaust flow, the ejector duct behaves exactly like an ejector–diffuser, with the PDE providing the primary flow and the surrounding atmosphere providing the secondary flow. In such cases, the PDE thrust augmentation performance should be expected to be the same as the ejector–diffuser described above.

Many experimental results for PDEs with ejector ducts have appeared in the open literature. Several of the most recent will be summarized here in order to support the general conclusions that follow. In all cases, the time-averaged experimental results were taken at their face value. As was foreseen, the published research relates only to stationary thrust augmentation. Although this is understandable, the experience documented in [6] makes it clear that the thrust augmentation at realistic flight speeds (where the energy conservation constraints on the internal flows, the captured momentum of the external flow, and the external drag on the ejector considerably reduce performance) will determine whether or not these devices will find practical application. It was also assumed that $\rho_p/\rho_s = 1$ throughout the ensuing calculations in order to make reasonable estimates of ϕ.

Reference [9] reports the results of a comprehensive experimental study on the performance of PDE-driven ejectors. Based on the geometrical information found in [9] the constant-area ejector [referred to in [9] as the straight PDE ejector (SE)] thrust augmentation as calculated from Eqs. (2) and (3) is 1.389, and the ejector–diffuser (referred to in [9] as the diverging PDE ejector or DE) has $\beta = 1.424$ and the thrust augmentation is calculated to be 1.740. The maximum measured SE thrust augmentation at the highest fill fraction is 1.19 and the maximum at any fill fraction is 1.28. The maximum measured DE thrust augmentation at the highest fill fraction is 1.51 and the maximum at any fill fraction is 1.65 (see Fig. 4 of [9]). The thrust augmentation of both the SE and DE increase with the length of the ejector until a maximum is reached, as usually happens in steady flow ejectors (see Fig. 7 of [9]). These PDE ejectors therefore approach, but do not exceed, the performance of the steady ejector–diffusers analyzed above.

Reference [9] devotes considerable attention to the influence of the initial fill fraction on PDEs without ejectors. The decrease of thrust and the increase of fuel-based specific impulse as fill fraction ff decreases have been shown to be a manifestation of another form of thrust augmentation, namely the highly efficient transfer of the kinetic energy of the detonated fuel–air reactants to the axially adjacent nonreacting or inert material within the confines of the same tube (see [15,16]). These fundamental analyses demonstrated conclusively that impulse is proportional to $\sqrt{\mathrm{ff}}$ and fuel-based specific impulse is proportional to $\sqrt{1/\mathrm{ff}}$ (see Eq. 7 and Figs. 13 and 14 of [15] and Eq. 22 and Figs. 5 and 6 of [16]). The fill fraction ff should therefore be recognized as the impulse equivalent of $1/\sqrt{1 + m_s/m_p}$. These results are completely consistent with Eq. (1) and correlate the PDE thrust and fuel-based specific impulse vs fill-fraction data of Fig. 3 of [9].

Reference [10] reports appreciable thrust augmentation from flat-lip (4% tube wall thickness) PDE-driven constant-area ejectors (see Figs. 1 and 9 of [10]) that increases with tube length. Since the flat-lip constant-area ejectors have no surface area on which pressure can exert force in the axial or thrust direction, these results raise serious questions about the experimental techniques used in these unsteady thrust measurements.

Reference [11] employed a novel thrust plate method to determine the thrust augmentation of PDE ejector–diffusers. Although the ejectors included diffusers of unspecified and possibly significant area ratios (see Fig. 3 of [11]), the largest measured thrust augmentation was 2.05 for the ejector–diffuser and 2.50 for the tapered ejector (see Table 3 of [11]). The thrust augmentation increased as the ejector length and diffuser area ratio increased (see Figs. 5 and 8 and Table 1 of [11]), in accordance with Eqs. (2) and (3). Table 3 of [11] also shows that ejectors with diffusers have historically outperformed those without. This observation is frequently repeated in the PDE open literature without further investigation.

Reference [12] used the same experimental unsteady thrust measurement method as [11] but used a Hartmann–Sprenger tube rather than a PDE to create a primary flow (see Figs. 1 and 2 of [12]) at frequencies about 10 times the characteristic of PDEs. Although β is unspecified (but exceeds one), the highest measured thrust augmentation is 1.355 when $\alpha = 0.444$ and 1.376 when $\alpha = 0.250$ (see Table 3 of [12]). These thrust augmentation results are confirmed by the data presented in Fig. 5 of [12], which also shows that thrust augmentation increased with ejector length until a maximum is reached, as usually happens in steady flow ejectors.

Reference [13] presents useful data and insightful explanations regarding pressure distributions in PDE ejectors (see Fig. 2 of [13]). Figure 7 of [13] shows the measured changes in static pressure distribution throughout the ejector due to the increased secondary mass flow caused by the addition of a diffuser, especially the decreased static pressure at the diffuser entrance, and the increased suction on the surfaces of the entrance bellmouth (thrust) and the exhaust diffuser (drag). Figure 11 of [13] shows that the thrust augmentation calculated by integration of the measured pressure distribution never exceeds 1.50, despite the presence of an unspecified diffuser.

References [13,14] present flow visualizations (see Fig. 6 of [13] and Fig. 6 of [14]) that indicate that the transient flow establishment time of the PDE ejector cycle is a small fraction of the total operating cycle time. This suggests that the PDE ejector behavior is similar to the steady state for much of the operating cycle. Reference [14] also offers the attractive possibility of testing PDE ejectors under flight conditions, although the stated upper limit of a Mach number of 0.3 is considerably less than the normally encountered flight speeds. Special care should be taken to account for the probable change of primary stagnation pressure with flight condition.

Taken together, these experimental results point to a conclusion similar to that reached for the quasi-steady devices. That is, experimental results for unsteady PDE ejectors suggest that their thrust augmentation behavior is very similar to ejector–diffusers, as described by Eqs. (2), (3), and (5), which is considerably less than the perfect energy exchange of Eq. (1). Any implied performance improvement over constant-area ejectors could equally be attributed to enhanced initial mixing, exhaust diffuser area ratio (e.g., Fig. 4 of [9]), and/or experimental uncertainty. Designers should therefore expect the behavior of these devices to be similar to that of ejector–diffusers.

IV. Conclusions

1) The addition of a diffuser can increase the thrust augmentation of constant-area ejectors significantly (see Fig. 2b). Therefore, in order to properly comprehend and evaluate the behavior of steady or unsteady ejectors, the diffuser area ratio and the corresponding thrust augmentation must be specified and accounted for in future research. An important corollary to this observation is that the designers of ejectors should consider the diffuser area ratio as one of their most important design choices. Another important corollary is that experiments can and should be preceded by relevant predictions (cf. [5]).

2) Thrust augmentation is primarily the result of the spreading of the energy resident in the primary flow to the secondary flow, the latter usually being taken from the ambient surroundings. Ejector thrust augmentation is therefore constrained by conservation of energy, as represented by Eq. (1).

3) The desirable goal of controlled, predictable, highly efficient transfer of energy from the primary flow to the secondary flow by unsteady phenomena has yet to be fully attained by ejectors. Instead, previous research results suggest that unsteady ejector devices possess thrust augmentation performance characteristic of ejector–diffusers.

4) The PDE fill-fraction behavior results from a related thrust augmentation phenomenon, namely the highly efficient transfer of the kinetic energy of the detonated fuel–air reactants to the axially adjacent nonreacting or inert material within the confines of the same tube.

5) The thrust augmentation of unsteady ejectors at representative flight conditions must be investigated and understood if they are ever to find practical application.

Acknowledgments

The author is appreciative of the financial support provided to this project by the Department of Aeronautics (DFAN) of the U.S. Air Force Academy (USAF), for the productive climate created by DFAN and the Aeronautics Laboratory, and for the competent administrative support provided by the Digital Consultant Services, Inc. The author also wishes to thank Jack D. Mattingly and Walter M. Presz Jr. for the valuable support they provided during the course of this study and Benjamin D. Zumstein of the USAF for generating computations and figures.

References

[1] Heiser, W. H., "Thrust Augmentation," *Journal of Engineering for Power*, Vol. 89, Series A, No. 1, Jan. 1967, pp. 75–82.

[2] Heiser, W. H., and Pratt, D. T., *Hypersonic Airbreathing Propulsion*, AIAA Education Series, AIAA, Washington, D.C., 1994.

[3] Bussing, T., and Pappas, G., "Pulse Detonation Theory and Concepts," *Developments in High-Speed-Vehicle Propulsion Systems*, AIAA Progress Series, edited by S. N. B. Murthy, and E. T. Curran, Vol. 165, AIAA, Reston, VA, 1996, pp. 421–472.

[4] Presz, W. M., Jr., Reynolds, G., and Hunter, C., "Thrust Augmentation with Mixer/Ejector Systems," AIAA Paper 2002-230, 2002.

[5] Quinn, B., "Compact Ejector Thrust Augmentation," *Journal of Aircraft*, Vol. 10, No. 8, 1973, pp. 481–486.
doi:10.2514/3.60251

[6] Presz, W. M., Jr., Reynolds, G., and McCormick, D., "Thrust Augmentation Using Mixer-Ejector-Diffuser Systems," AIAA Paper 94-0020, Jan. 1994.

[7] Foa, J. V., *Elements of Flight Propulsion*, Wiley, New York, 1960.

[8] Porter, J. L., and Squyers, R. A., "A Summary/Overview of Ejector Augmentor Theory and Performance," Vought Corp., Advanced Technology Center, Rept. R-91100/CR-47A, Dallas, TX, 1979.

[9] Allgood, D., Gutmark, E., Hoke, J., Bradley, R., and Schauer, F., "Performance Measurements of Pulse Detonation Engine Ejectors," AIAA Paper 2005-223, Jan. 2005.

[10] Landry, K., Shehadeh, R., Lee, S.-Y., Pal, S., and Santoro, R. J., "Effect of Operating Frequency on PDE Driven Ejector Thrust Performance," AIAA Paper 2005-3832, July 2005.

[11] Wilson, J., Sgondea, A., Paxson, D., and Rosenthal, B. N., "Parametric Investigation of Thrust Augmentation by Ejectors on a Pulsed Detonation Tube," AIAA Paper 2005-4208, July 2005.

[12] Wilson, J., "Effect of Pulse Length and Ejector Radius on Unsteady Ejector Performance," *Journal of Propulsion and Power*, Vol. 23, No. 2, 2007, pp. 345–352.
doi:10.2514/1.19665

[13] Glaser, A. J., Caldwell, N., Gutmark, E., Hoke, J., Bradley, R., and Schauer, F., "Experimental Study of Ejectors Driven by a Pulse Detonation Engine," AIAA Paper 2007-447, Jan. 2007.

[14] Caldwell, N., Gutmark, E., Hoke, J., Bradley, R., and Schauer, F., "Investigation of Fundamental Processes Leading to Pulse Detonation Engine/Ejector Thrust Augmentation," AIAA Paper 2008-116, Jan. 2008.

[15] Sato, S., Matsuo, A., Endo, T., and Kasahara, J., "Numerical Studies on Specific Impulse of Partially Filled Pulse Detonation Rocket Engines," *Journal of Propulsion and Power*, Vol. 22, No. 1, 2006, pp. 64–69.
doi:10.2514/1.9514

[16] Endo, T., Yatsufusa, T., Taki, S., Matsuo, A., Inaba, K., and Kasahara, J., "Homogeneous-Dilution Model of Partially Fueled Simplified Pulse Detonation Engines," *Journal of Propulsion and Power*, Vol. 23, No. 5, 2007, pp. 1033–1041.
doi:10.2514/1.21223

K. Frendi
Associate Editor