References

[1]Fancher, R. B., "Low-Area Ratio, Thrust-Augmenting Ejectors," *Journal of Aircraft*, Vol. 9, No. 3, March 1972, pp. 243–248.

[2]Heiser, W. H., "Thrust Augmentation," ASME Paper 66-GT-116, Zurich, Switzerland, March 1966.

Reply to Comment by Philip A. Graham

Paul M. Bevilaqua*

Aerospace Research Labs. Wright-Patterson Air Force Base, Ohio

GRAHAM is correct in observing that Eqs. (1) and (4) of the original paper refer only to the zero diffusion case; this was all they were intended to do, since they describe the performance of the simple ejector shown in that work. A development with diffusion was not included, as it can be found in a number of the sources referenced. Inclusion of a perfect diffuser results in Graham's Eq. (4).

Figure 2 of the original work is incorrect. In redrawing this figure from the source paper[3] an error was made. Figure 2 of the source paper gives Graham's computed values. We accept full responsibility for this error.

In the Aerospace Research Laboratories' thrust augmentation concept the source of the primary flow is envisioned as the bypass air from a turbofan engine, and so there is no significant density difference between the mixing flows. The incompressible analysis is therefore appropriate. However, it should be understood that Heiser's[2] analysis only considers the effect of the density difference. A hotter primary jet would have a lower density, but it would also be more viscous. The net effect on the level of augmentation cannot be predicted by the simple analyses presently in use.

Graham has questioned the experimental results. The basis of his objection is his belief that the nozzle was 24.5 in. long. This dimension was unfortunately added to the figure by the Journal editors. The actual nozzle length was 36 inches which could be computed from the text which states "A unique feature is the "hypermixing" primary nozzle which is segmented into 24 elements 1½ in. long." Using the 36 in. figure for this length and the 12.6 square in. for the area, one obtains W_0 = 0.35 inches, slightly less than 0.38 as Graham correctly implies it should be.

No reference was made to a "loss free" ejector as Graham's use of quotation marks implies. In fact a significant portion of the mixing section of Fancher's work is devoted to a discussion of the transfer efficiency associated with the mixing loss. This loss is implicitly accounted for in the definition of thrust augmentation ϕ, since the momentum flux from the ejector reflects the transfer efficiency of the mixing process.

Regarding the definition of augmentation, Graham has chosen a different reference thrust than the one used by Fancher. The augmentation can be defined in terms of the thrust of the unshrouded primary nozzle, but then ejectors with different primary nozzles cannot be directly compared. A better definition is the one used by Fancher in which the reference thrust is the value computed for an isentropic expansion of the primary mass to atmospheric pressure. Ejectors can thus be compared in terms of thrust per horsepower required. More importantly, the nozzle efficiency becomes part of the design optimization. The development of the hypermixing nozzle is a consequence of this approach, since it was felt at ARL that an improvement in the performance of short aircraft ejectors could be obtained by increasing the rate of entrainment, even at some cost in nozzle efficiency.

Graham has misunderstood the basic conclusion that can be drawn from this work. The effect of hypermixing is not to improve the performance of a given low area ratio ejector in the sense of bringing it closer to the ideal. In fact, the lower velocity efficiency of hypermixing nozzles is a penalty that must be paid for their use. What is achieved is a higher thrust augmentation in an ejector of given length, a short length that is practical for aircraft installation. This is important to understand. The best ejector performance at a given area ratio is obtained when mixing is complete. This can be achieved either with a long mixing duct, which prohibits aircraft installation, or in a lesser distance with hypermixing nozzles at some penalty in maximum augmentation.

The comparison between two ejectors of identical geometry except for the hypermixing nozzle has been performed at ARL by Bevilaqua.[4] The results of this test are summarized in the figure. The isentropic thrust of the primary flow is used to define the augmentation. It can be seen that at low diffuser area ratios, the slot nozzle produces larger values of augmentation than either of the hypermixing nozzles. However, as the diffuser angle is increased further, the diffuser in the configuration assembled with the slot nozzle stalls, and there is a resultant loss in performance. Both hypermixing nozzles give higher maximum augmentation than the slot nozzle. These results have been discussed at length in Ref. 4.

In conclusion, we would like to apologize for the error in the original article and any confusion it may have caused. We also wish to thank Mr. Graham for his comments.

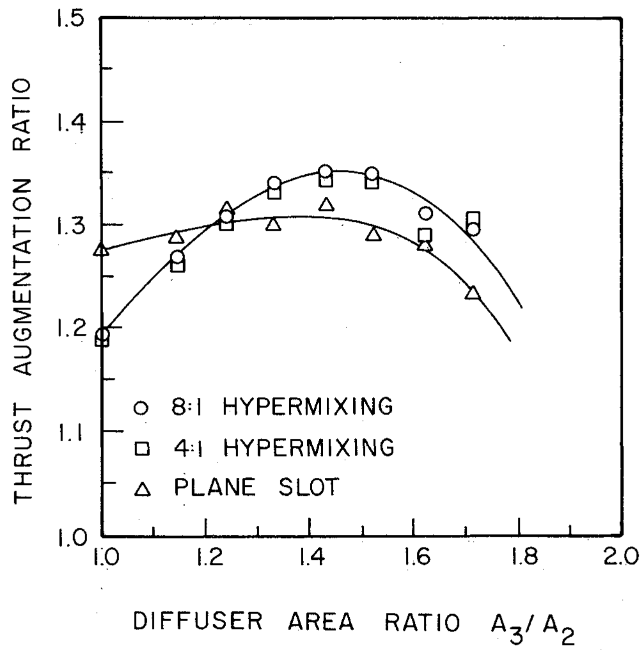

Fig. 1 Performance of the inlet area ratio 6.5 ejector. The hypermixing nozzles improve augmentation by making efficient diffusion of the mixed flow possible.

Received June 9, 1973.

Index categories: Subsonic and Supersonic Air Breathing Propulsion; Jets, Wakes and Viscid—Inviscid Flow Interactions; Nozzle and Channel Flow.

*Aerospace Engineer; replying for Richard Faucher who is presently with Pacific Gas and Electric Company.

They have been helpful in pointing out some areas of misunderstanding concerning this work and provoked a stimulating exchange which we hope has been of interest to other investigators in this area.

References

[1]Fancher, R. B., "Low Area Ratio Thrust Augmenting Ejectors," *Journal of Aircraft,* Vol. 9, No. 3, March 1972, pp. 243–248.

[2]Heiser, W. H., "Thrust Augmentation," *Journal of Engineering for Power,* Jan. 1967, pp. 75–82.

[3]Fancher, R. B., "Low Area Ratio Thrust Augmenting Ejectors," AIAA Paper 71–576 Palo Alto, Calif., 1971

[4]Bevilaqua, P. M., "An Evaluation of Hypermixing for V/STOL Aircraft Augmentors," AIAA Paper 73-654, Palm Springs, Calif., 1973.

Comments on the Comment by Philip A. Graham and Reply by Paul M. Bevilaqua

William K. Greathouse*

Grumman Aerospace Corp., Bethpage, N.Y.

GRAHAM'S very complete analysis of Fancher's paper pointed out an error in the presentation of ejector potential (ideal) augmentation ratio (Fig. 2), questioned the primary nozzle area (size) used in the experiment and observed that something was missing from the Eq. (11) used to define augmentation ratio with inlet and nozzle losses. He also noted that Fancher's equations were developed for a unique case of equal flow densities ($\rho_0 = \rho_1$) rather than the case of a hot primary (nozzle) flow.

Bevilaqua's reply verified a plotting error in Fig. 2, explained the nozzle area question (a wrong dimension in Fig. 6) and pointed out that Graham used a different reference thrust than did Fancher in the definition of ejector augmentation ratio.

These additional comments are offered to clarify Fanchers Eq. (11), point out why Graham's Eq. ($\overline{11}$) is different and to include some remarks on the effects of hot nozzle flow.

Received July 26, 1973; revision received September 7, 1973.

Index categories: Air Breathing Propulsion, Subsonic and Supersonic; Jets, Wakes, and Visced—Invisced Flow Interactions; Nozzle and Channel Flow.

*Propulsion Section Head. AIAA Journal of Aircraft Associate Editor (1964–1972).

The augmentation ratio, ϕ, for a static ejector system using incompressible fluids of the same density, an unchoked primary nozzle, a constant area mixing section and a full flowing diffuser discharging an ambient pressure is (using Fancher's nomenclature)

$$\phi = \eta_N(1 + xu)^2(A_2/A_3)/(x + 1)[1 - (1 + \xi_1)\eta_N{}^2u^2]^{1/2} \tag{A}$$

One may assume that Fancher did not include the $(1 + \xi_1)\eta_N{}^2$ term in his Eq. (11) because the product was almost unity ($= 0.939$ for $\xi_1 = 0.04$, $\eta_N = 0.95$) for the hypermixing ejector being tested.

Substituting Graham's nomenclature in Eq. (A) gives

$$\phi = (\bar{\eta}_N)^{1/2}(1 + xu)^2(A_2/A_3)/(x + 1)[1 - (\bar{\eta}_N/\eta_I)u^2]^{1/2} \tag{B}$$

where

$$\bar{\eta}_N = \eta_N{}^2\ , \quad \eta_I = 1/(1 + \xi_1)$$

Graham's Eq. ($\overline{11}$) is identical with Eq. (B) except for the first term, $(\bar{\eta}_N)^{1/2}$. The reason this term does not appear in Graham's equation is because he used a different definition of V_0' in the thrust reference for augmentation ratio. Francher used the conventional definition of isentropic velocity for V_0'. Graham used V_0' as the velocity from an actual nozzle having the same thrust efficiency as the nozzle employed in the ejector system.

Note that nothing is technically wrong with the definition used by Graham since it is still a matter of choice as to what reference is employed for augmentation ratio, ϕ. And it is a very simple matter to convert from Graham's ϕ to Fancher's ϕ using nozzle velocity coefficient $[C_V = \eta_N = (\bar{\eta}_N)^{1/2}]$ as the conversion factor. In the past, several references have been used for ϕ in ejector systems that employed choked convergent nozzles or underexpanded convergent-divergent nozzles. The conventional isentropic velocity reference (as used by Fancher) has well served as an unofficial "standard" for over 20 years and (as noted by Bevilaqua) should be employed for evaluating or comparing different type ejector systems on an absolute basis.

As for the effects of hot nozzle flow on ejector thrust augmentation, it should be noted that the simple incompressible flow equations presented in Fancher's paper were never intended for such application. Hot nozzle flow can be accounted for by using the compressible flow relationships and the task is best handled today with computer programs. Hand calculations may be performed for one-dimensional steady compressible flow using the analysis presented in Ref. 1. In general, augmentation ratio of an ideal ejector is degraded by the use of a hot nozzle flow. In real ejectors the degradation may be greater or less depending on how the loss factors change with hot flow.

References

Turner, R. L. et al.,"Charts for the Analysis of One-Dimensional Steady Compressible Flow," TN 1419, Jan. 1948, NACA.