

NONSTEADY-FLOW THRUST AUGMENTING EJECTORS

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This note concerns those ejector augmenters in which the transfer of mechanical energy from the primary to the secondary flow takes place, at least in part, through the work of interface pressure forces. This mode of energy transfer, commonly referred to as "pressure exchange", is of interest in that the work of interface pressure forces is essentially nondissipative. It requires, however, that the interacting flows be nonsteady, because no work is done by pressure forces acting on a stationary interface.

The potential superiority of nonsteady-flow processes from the standpoint of energy transfer efficiency is also predicted by the energy equation,

$$\frac{1}{\rho} \frac{DH}{Dt} = \frac{1}{\rho} \frac{\partial p}{\partial t} + \vec{f} \cdot \vec{V} \quad (\text{for incompressible flow})$$

or

$$\frac{Dh^\circ}{Dt} = T \frac{Ds}{Dt} + \frac{1}{\rho} \frac{\partial p}{\partial t} + \vec{f} \cdot \vec{V} \quad (\text{for compressible flow})$$

where \vec{f} is the resultant of body and surface viscous forces per unit mass, h° the specific stagnation enthalpy, H the total head, p the pressure, s the specific entropy, T the temperature, \vec{V} the particle velocity, and ρ the density [1, 2, 3]*. These equations show that, in the absence of body forces, the energy level of a particle in a flow can be changed reversibly only if the flow is nonsteady.

* Numbers in brackets designate References at the end of paper.

Of special interest in this connection are the results of a remarkable series of experiments conducted by Lockwood [4], where it was shown that the pulsating-flow ejector is capable of higher energy transfer efficiencies than its steady-flow counterpart, with greatly reduced interaction lengths (see Figs. 1 and 2). These results could, however, be misleading. The pulsating-flow ejector is clearly a promising arrangement when one deals with a primary that is pulsating to begin with -- e.g., with the exhaust of a pulsejet. But when the pulsation of the primary has to be obtained by "chopping up" an originally steady flow, the theory predicts -- and Lockwood's experiments have confirmed -- that the losses associated with the chopping up of the primary can be large enough to more than offset the thrust increment that is produced in the augmenter. Similar losses, in addition to analytical and control difficulties, are encountered in the design and operation of all flow induction devices based on the utilization of wave processes.

On the other hand, a steady flow can be transformed into a nonsteady one without chopping up or other losses, through the simple artifice of a change of frame of reference. A flow field that is not uniform throughout can be steady in, at most, only one coordinate system. An observer moving relative to this unique coordinate system will see the flow as nonsteady. We apply the designation "cryptosteady" to a process which is nonsteady but admits a frame of reference in which it is steady. The special merit of cryptosteady interactions is that they can be generated, controlled, and analyzed as steady-flow processes in that unique frame of reference

F_s in which they are steady, while retaining the efficiency advantages of nonsteady-flow processes in the frame of reference F_u in which they are utilized.

The simplest embodiments of this concept are those in which F_s rotates at constant angular velocity relative to F_u . In the "rotary jet" augmenter configuration (Fig. 3), the primary is discharged into the interaction space through skewed nozzles on the periphery of a free-spinning rotor, thereby driving the rotor and forming the helical rotating patterns that are referred to as "pseudoblades". The boundaries of the pseudoblades are the interfaces separating the primary from the secondary flow, and the pressure forces which the two flows exert on one another at these moving interfaces do work. Through this action, mechanical energy is extracted from the primary flow as in a turbine and is added to the secondary as through a fan or propeller. Since this "pressure exchange" component of the interaction is essentially nondissipative, the performance of the rotary jet can be expected to be better than that of the conventional steady-flow ejector. This fact had already been confirmed experimentally by Vennos at Rensselaer [5], by Avellone at Grumman [6], and by Hohenemser at McDonnell [7,8], prior to the start of the program of research that we have been carrying out on this subject at the George Washington University jointly with the U.S. Naval Academy for the past two years.

As for the theory, previous studies had been based primarily on two analytical models -- the two-dimensional and the thin-jet model. In the two-dimensional model [9] the penetration of the secondary flow into the spaces between the

pseudoblades is assumed to be completed before the two flows deflect each other to a common orientation in the rotor-fixed frame of reference (Fig. 4) and the depth of the interaction space is assumed to be small compared to its mean radius. This analytical model can be approximated in practice through the use of hooded nozzles (Fig. 5) or other design artifices. However, in the absence of such artifices the performance predictions of the two-dimensional theory must be viewed with caution. The other main approach available at the start of our current project was that of Homenemser's thin-jet strip theory [7], in which the primary is treated as a very thin jet successively interacting with infinitesimal layers of the secondary flow (Fig. 6). In each of these infinitesimal steps, as the two interacting flows deflect each other to a common orientation, the primary jet, which is finite, undergoes an infinitesimal deflection, and the secondary layer, which is infinitesimal, undergoes a finite deflection. The changes of angular momentum of the two flows in each step must be equal and opposite. The equation expressing this fact yields the distribution of deflections and velocities at the exit from the interaction space, and therefore also the thrust augmentation ratio.

A more realistic analytical model has recently been developed, whereby account is taken of that part of the interaction that takes place where the secondary flow enters the space between the pseudoblades. As Fig. 7 shows, different layers in both flows undergo different histories, different deflections, and different exchanges of mechanical energy.

A detailed study of the interaction according to this model has been carried out by Costopoulos (Ref. 10).

Fig. 8 shows a comparison of the performance predictions of the above-mentioned theories.

Fig. 9, also from Ref. 10, shows what happens when any appreciable mixing is allowed to take place during the deflection phase. The effect is in this case always an adverse one, as one would expect, since any energy that is transferred through mixing during the deflection phase is energy that could have been transferred more efficiently by pressure exchange.

In contrast, and contrary to previous results, Costopoulos (Ref. 12) has found that mixing after the mutual deflection phase is always beneficial if no account is taken of the drag and weight penalties that are associated with the required extension of the shroud. Actually, beyond a certain spin angle, the benefit that can be derived from mixing becomes too small to offset these penalties.

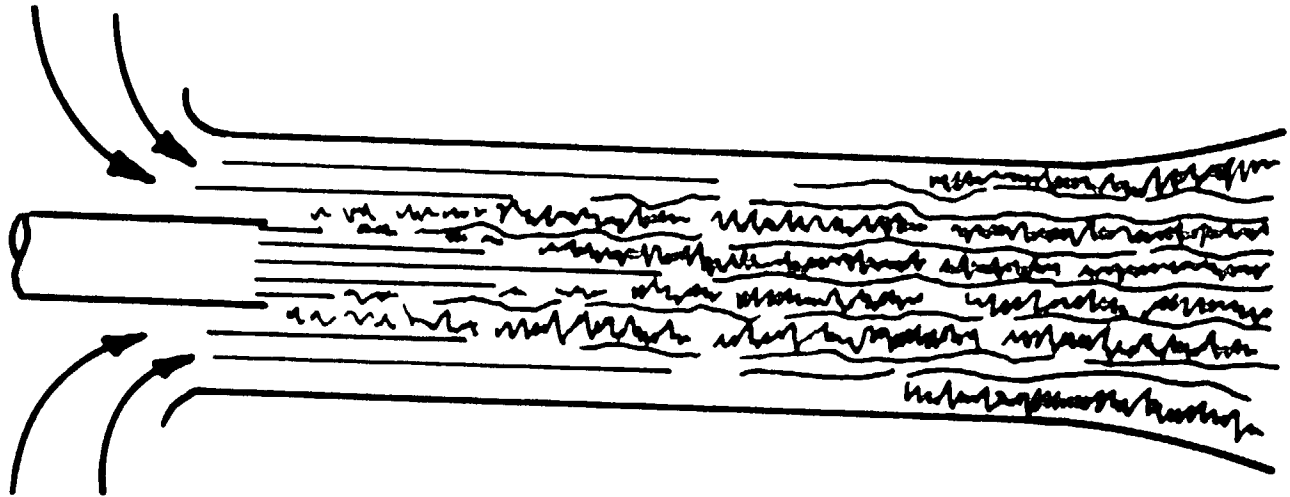
In a separate study (Ref. 11), a "black box" approach was used to show that the superiority of the rotary jet over the ejector can be explained as an effect of pressure exchange alone, quite apart from whatever benefit may be derived from the enhancement of mixing. The same paper also considered the effect if secondary-to-primary density ratio and showed that the effect of increasing this ratio may be beneficial or

adverse, depending on the magnitude of a parameter called "pressure exchange amplitude", which is a measure of the vigor of the collision. This study was continued in Ref. 12, with the interesting result that, whereas in the ejector the best density ratio is 1.0, in the rotary jet, beyond a relatively low spin angle, the effect of an increase of density ratio is always beneficial (Fig. 10).

References

1. Eck, B., "Technische Strömungslehre," Julius Springer, Berlin, 1957, p. 50.
2. Dean, R. C., Jr., "On the Necessity of Unsteady Flow in Fluid Machines," Journal of Basic Engineering, March 1959, pp. 24-28.
3. Foa, J. V., "Pressure Exchange," Applied Mechanics Surveys, Spartan Books, 1966, pp. 1177-1183.
4. Lockwood, R. M., "Energy Transfer from an Intermittent Jet to an Ambient Fluid," Hiller Aircraft Co., Summary Report No. ARD-238, June 30, 1959.
5. Foa, J. V., "The Bladeless Propeller," Proc. of Seventh Symposium on Naval Hydrodynamics, Rome, Italy, 1968, ONR, DR-148, pp. 1351-1372.
6. Avellone, G., "Theoretical and Experimental Investigation of the Direct Exchange of Mechanical Energy Between Two Fluids," Grumman Research Dept. Memorandum RM 365, June 1967.
7. Hohenemser, K. H., "Preliminary Analysis of a New Type of Thrust Augmenter," Proceedings of the 4th U.S. National Congress of Applied Mechanics, ASME, New York, 1962, pp. 1291-1299.
8. Hohenemser, K. H., "Flow Induction by Rotary Jets," Journal of Aircraft, Vol. 3, No. 1, Jan.-Feb. 1966, pp. 18-24.
9. Foa, J. V., "Cryptosteady Pressure Exchange," Rensselaer Polytechnic Institute Tech. Rept. TR-AE 6202, Troy, N.Y., March 1962.
10. Costopoulos, T., "A Wide-Jet Strip Analysis of Cryptosteady-Flow Thrust Augmenters-Parts 1 and 2," GWU Tech. Repts. TR-UTA-771 and 772, March 1977.
11. Foa, J. V., "Ejectors and Rotary Jets as Thrust Augmenters," article in Marine Propulsion, edited by J. Sladky, Jr., ASME Ocean Engineering Division, December 1976.
12. Costopoulos, T., "Constant-Area Flow Interactions in Cryptosteady-Flow Thrust Augmentors," GWU Tech. Repts. TR-UTA-773 and 774, April 1977.

STEADY-FLOW
EJECTOR



PULSATING-
FLOW EJECTOR

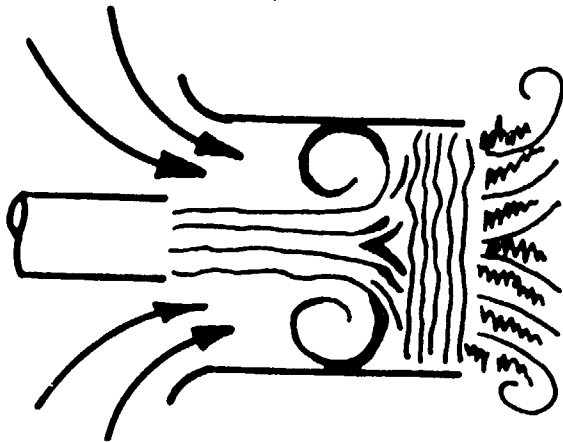


Figure 1.- Steady-flow and pulsating-flow ejectors (from ref. 4).

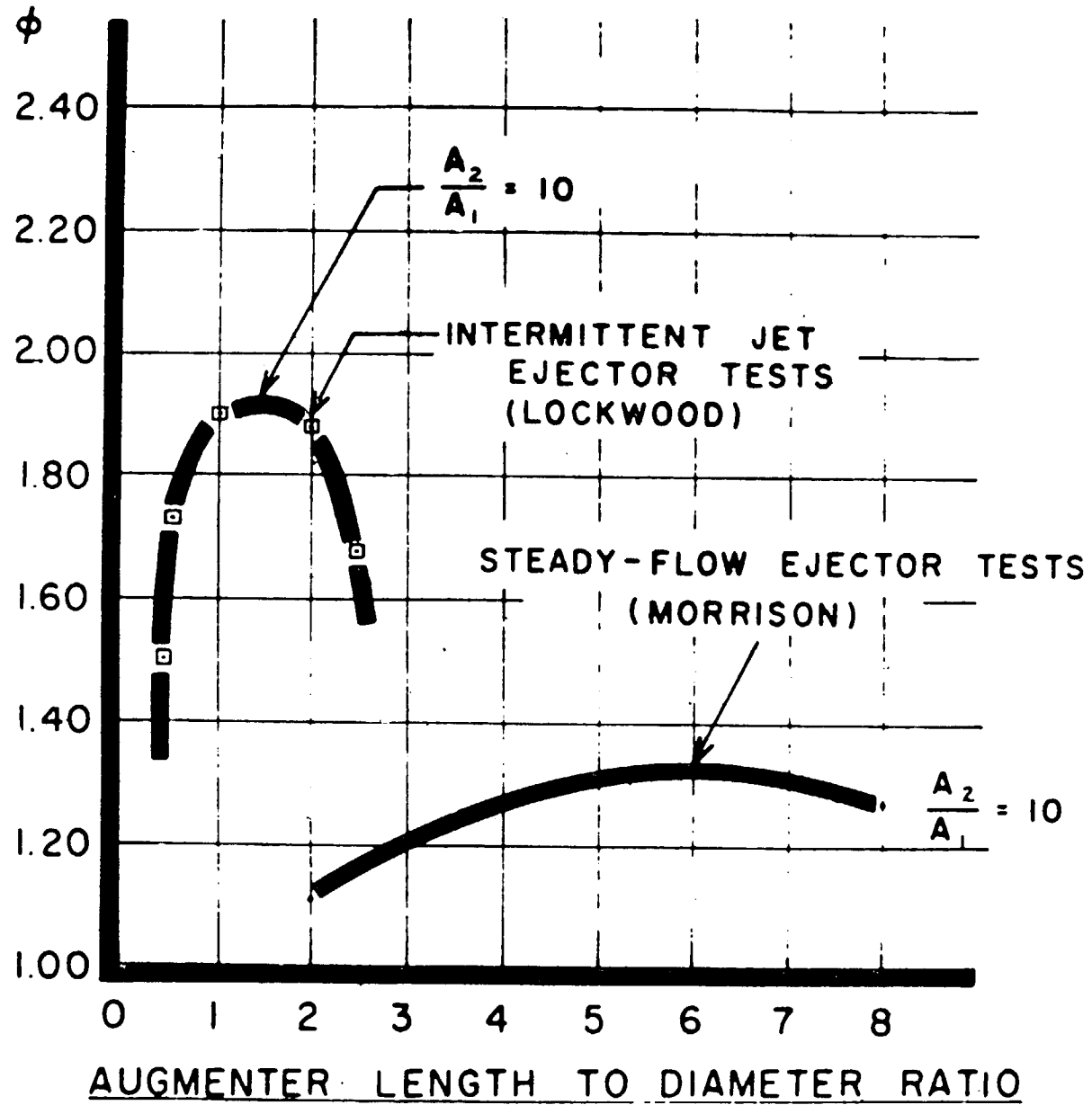


Figure 2.- Comparison of static thrust augmentation ratios of steady-flow and pulsating-flow ejectors (from ref. 4).

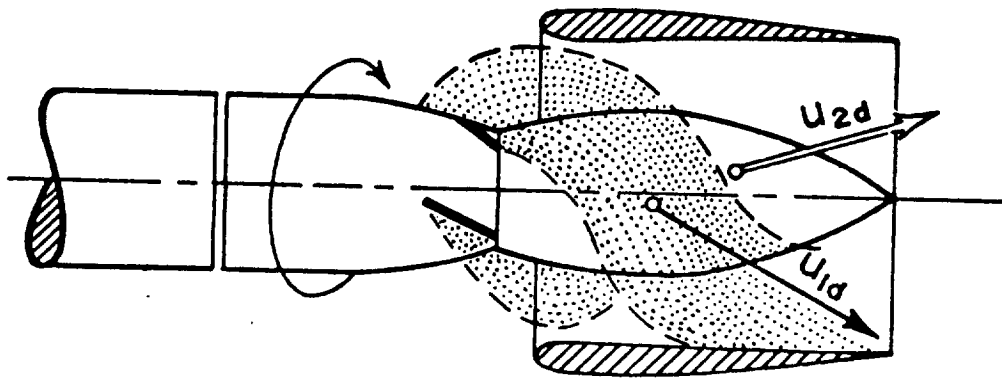


Figure 3.- Rotary-jet thrust augmenter.

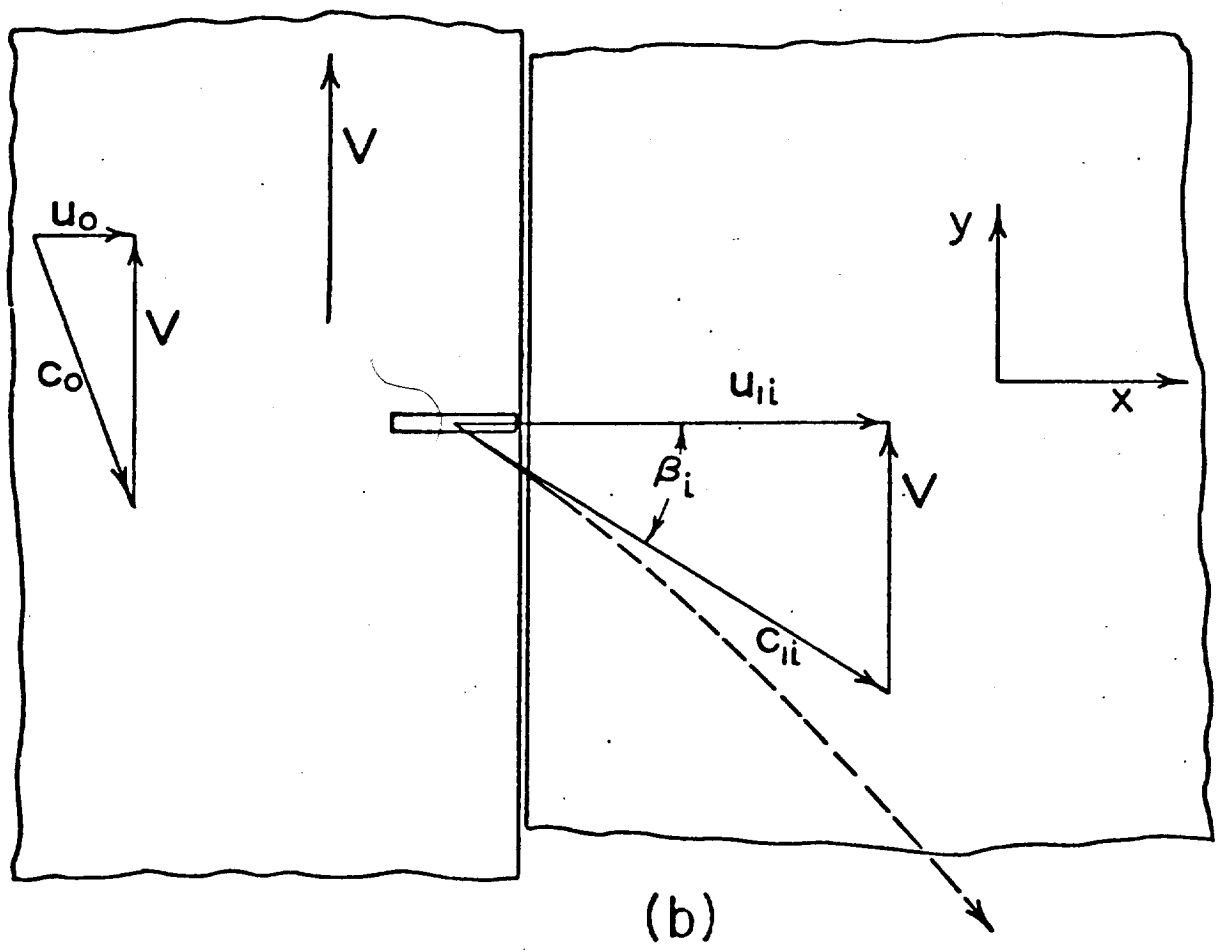
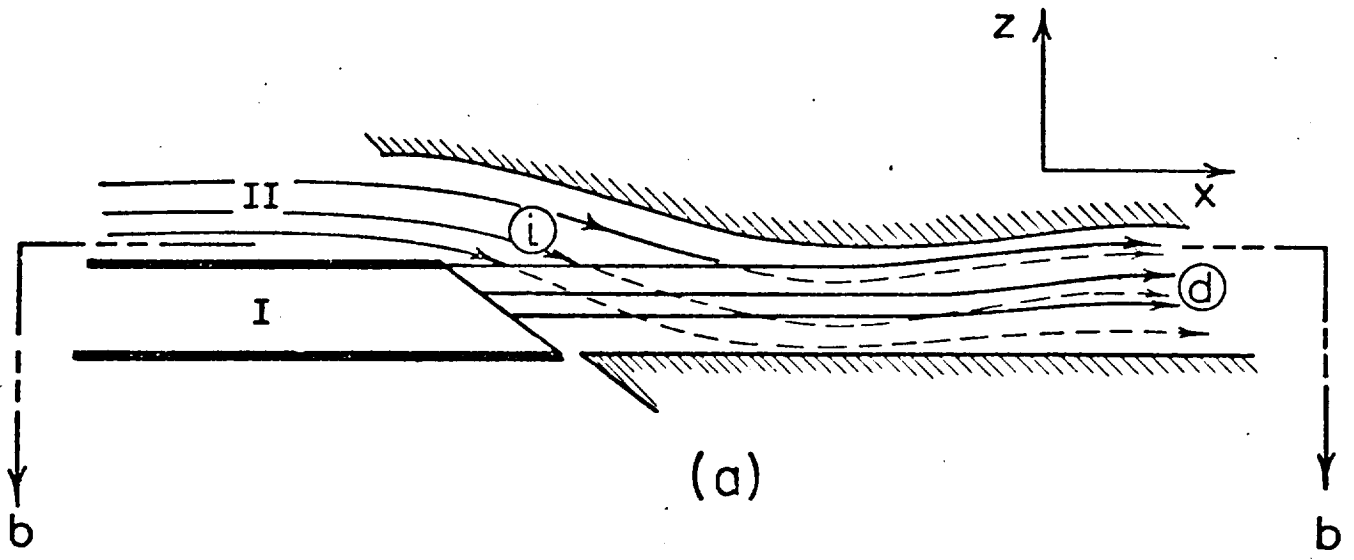


Figure 4.- Analytical model for two-dimensional theory.

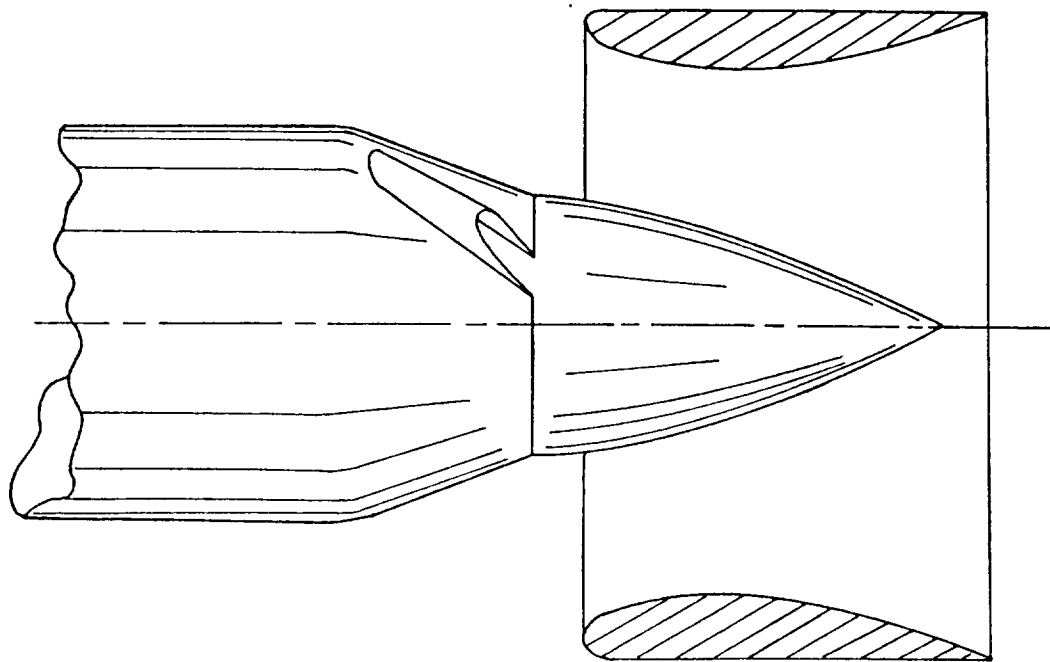
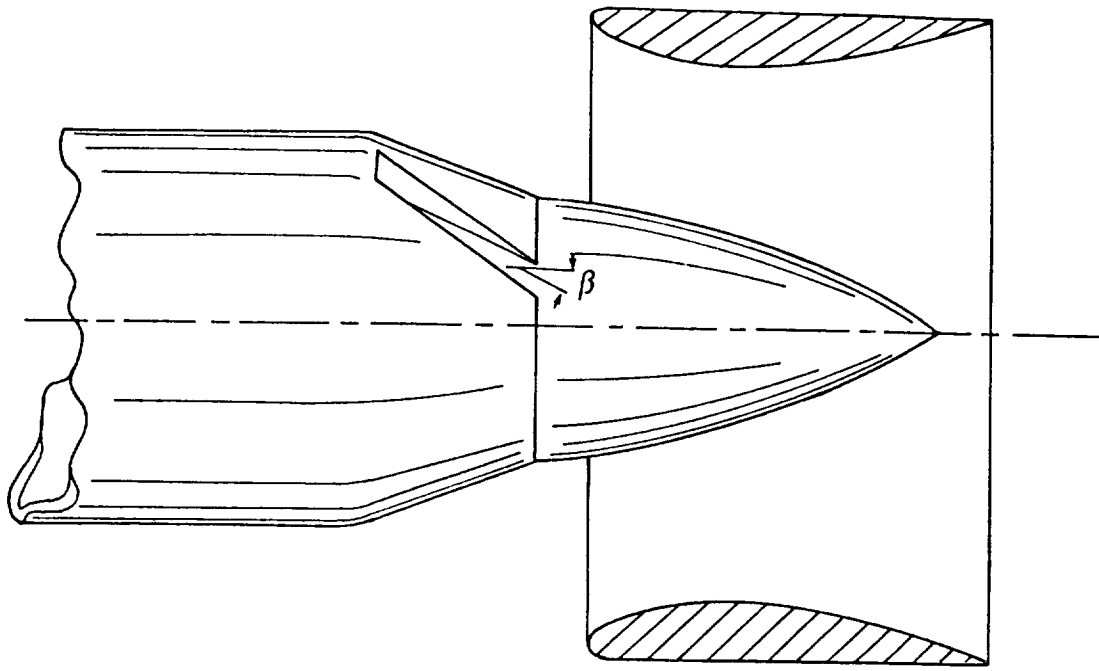


Figure 5.- Unhooded and hooded rotor nozzles.

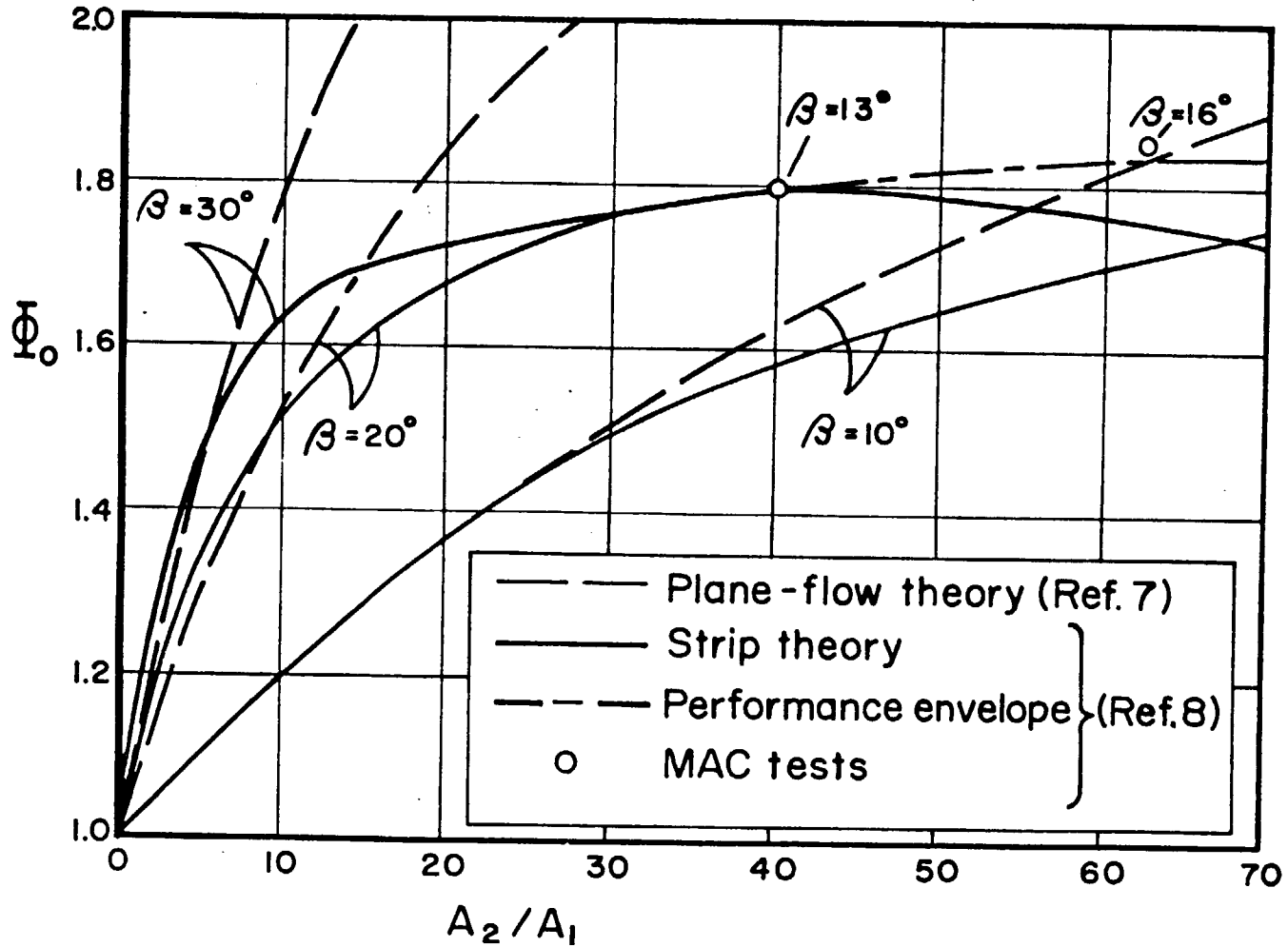
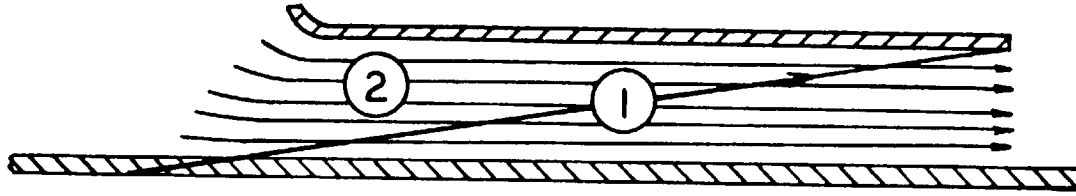


Figure 6.- Analytical model for thin-jet strip theory.

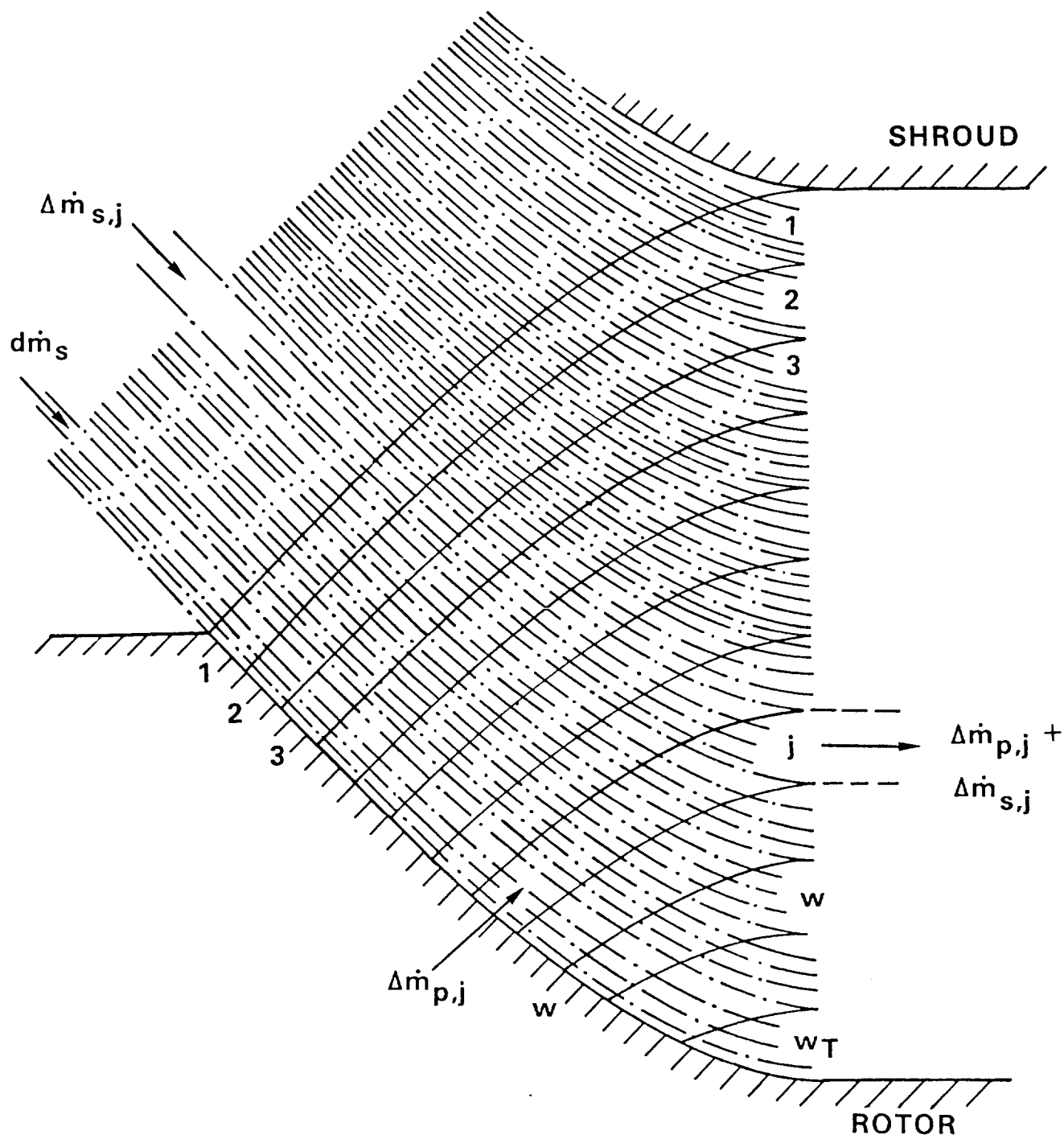


Figure 7.- Analytical model for wide-jet strip theory.

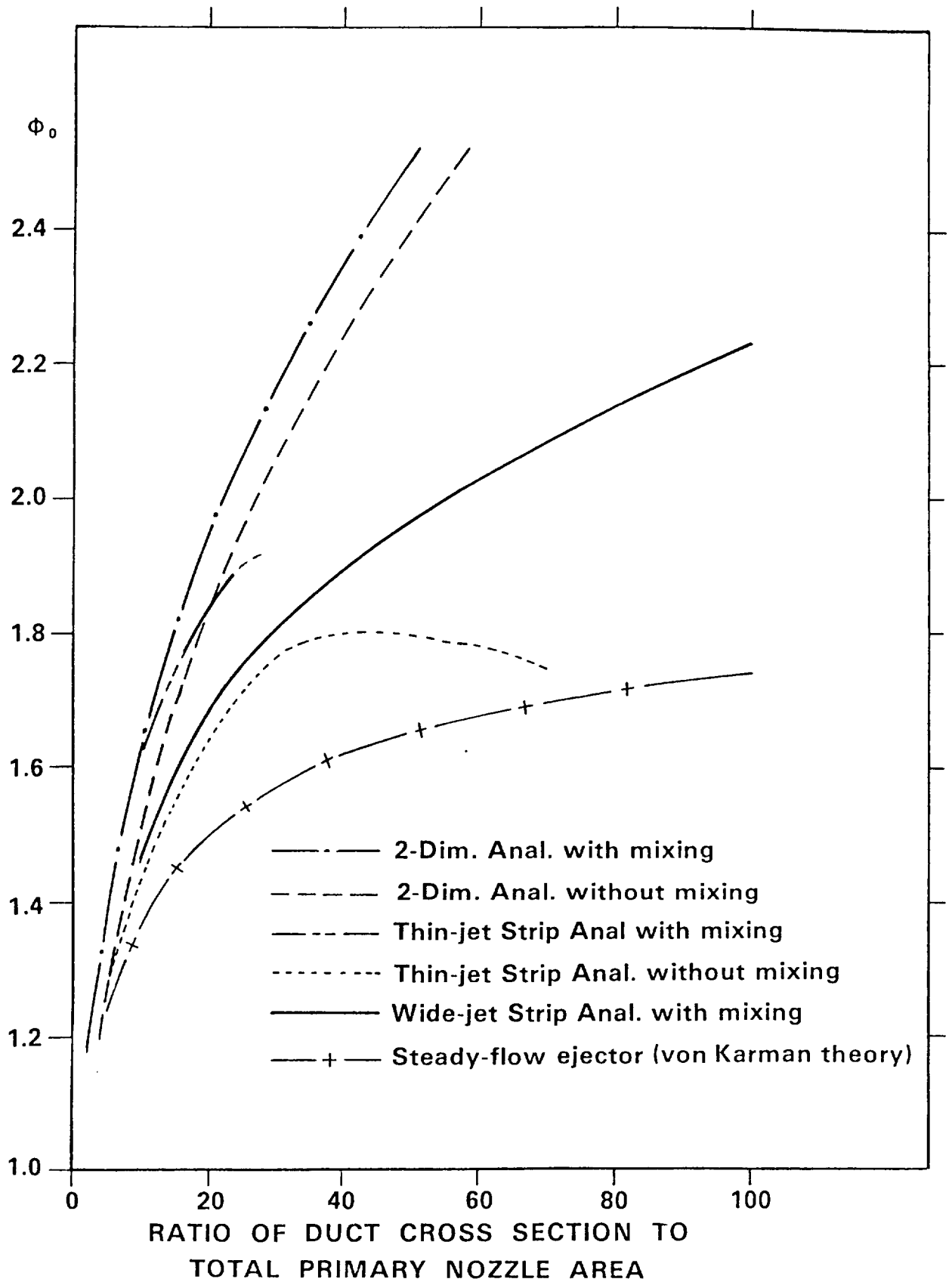


Figure 8.- Comparison of static thrust augmentation ratios predicted by various theories for constant-area interaction ducts and for a rotary-jet spin angle (inclination of primary nozzle axis to meridional plane) of 20°.

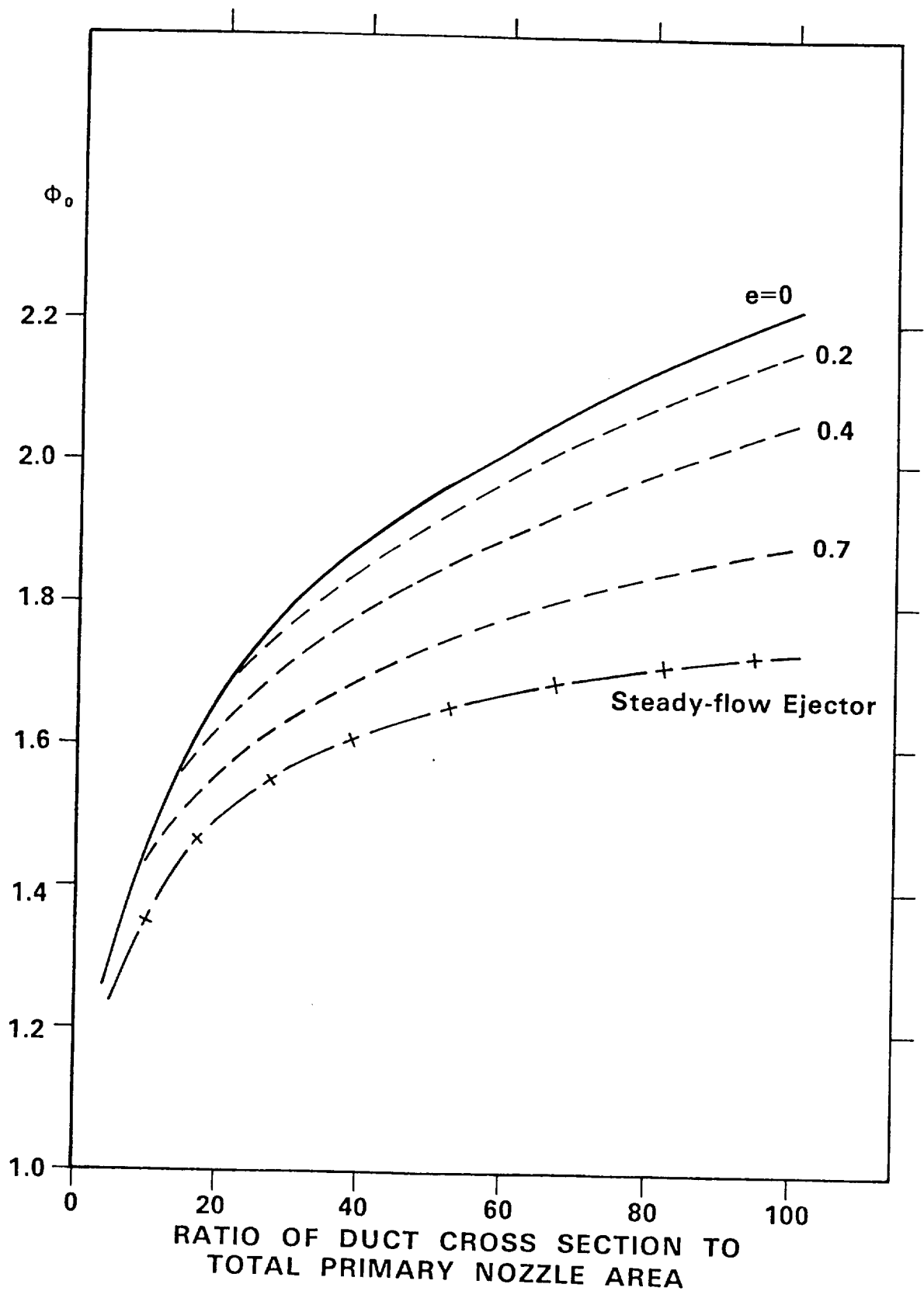


Figure 9.- Effect of mixing during pressure exchange. e = percentage of secondary flow entrained during pressure exchange. Rotary-jet spin angle = 20° .

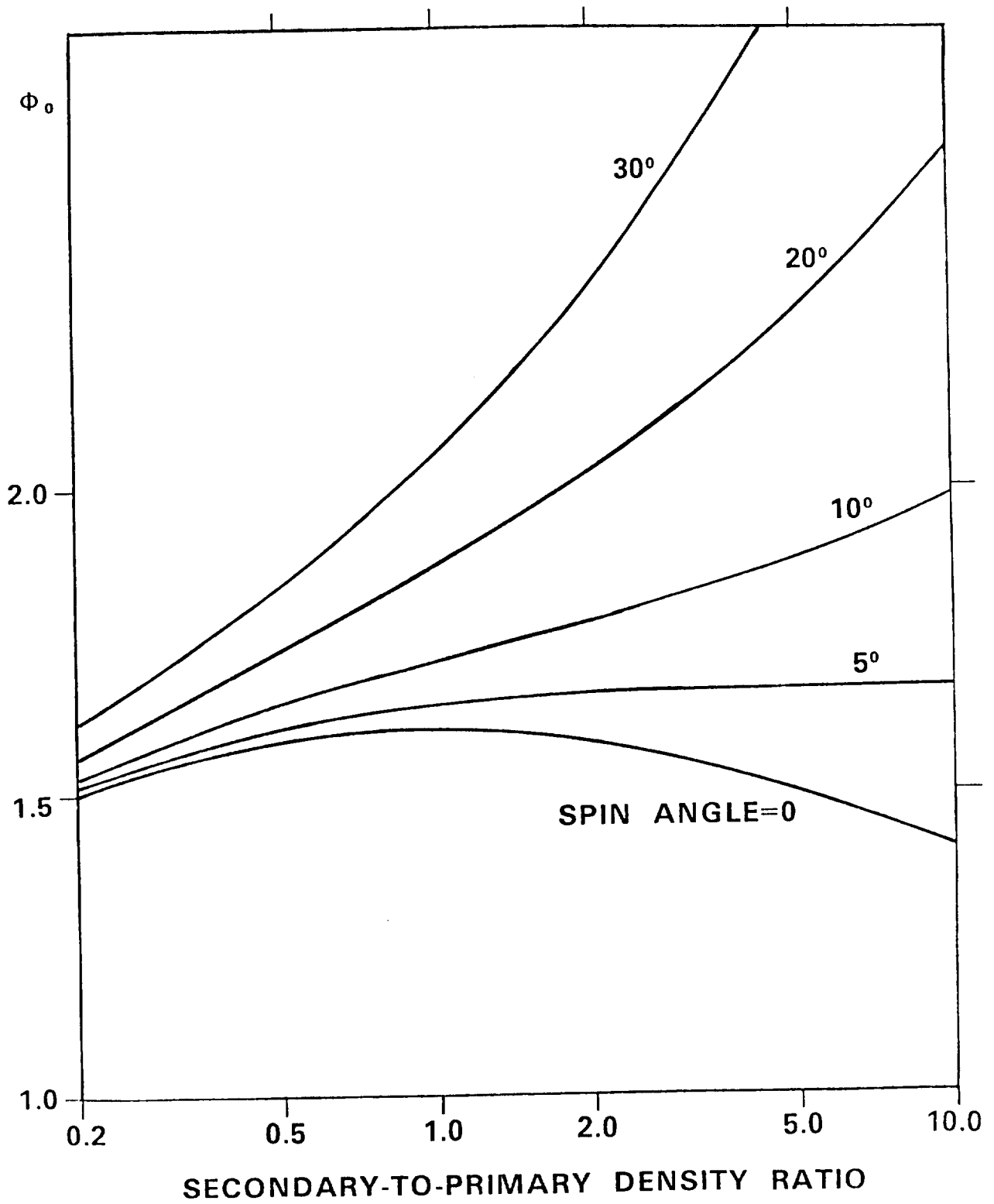


Figure 10.- Effect of secondary-to-primary density ratio on static thrust augmentation, for various spin angles. Constant-area interactions. Ratio of duct cross section to primary nozzle area = 30. Ratio of primary total pressure to ambient pressure = 1.5.