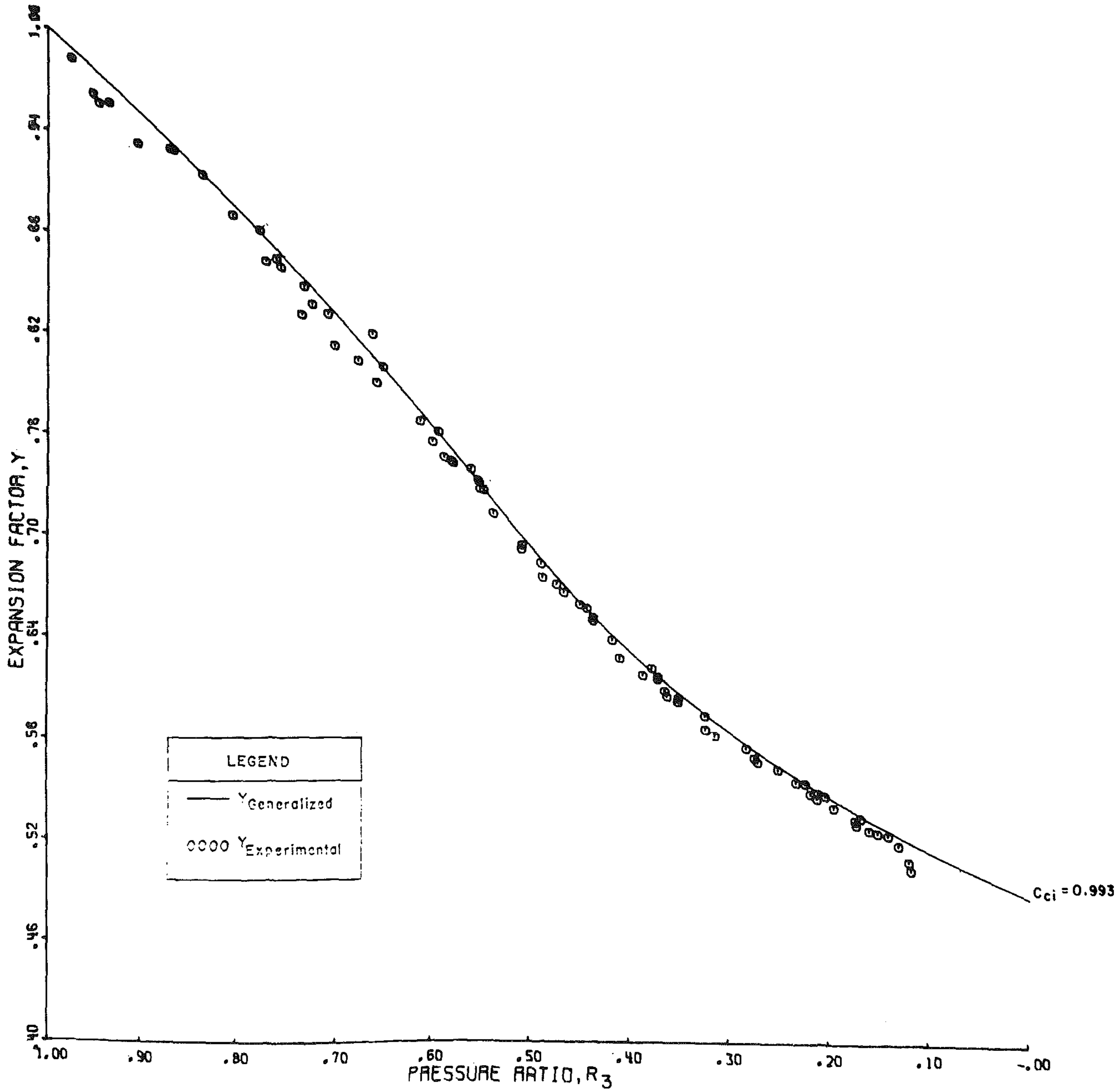

Fig. 7(d) β = 0.2406, HEI nozzle

References

1 *Fluid Meters—Their Theory and Application,* Report of ASME Research Committee in Fluid Meters, 5th ed., 1959.

2 Benedict, R. P., *Fundamentals of Temperature, Pressure, and Flow Measurements,* Wiley, 1969.

3 Marxman, G. A., and Burlage, H., "Expansion Coefficients for Orifice Meters in Pipes Less Than One-Inch in Diameter," Journal of Basic Engineering, Trans. ASME, Series D, Vol. 83, No. 2, June 1961, p. 289.

4 El Agib, A. A. R., "An Expression for the Coefficient of Velocity of Venturi-Meters," *Journal of Mechanical Engineering Science,* Vol. 10, 1968, p. 291.

5 Benedict, R. P., "Generalized Contraction Coefficient of an Orifice for Subsonic and Supercritical Flows," Companion ASME Paper No. 70-WA/FM-1, Dec. 1970.

6 Cunningham, R. G., "Orifice Meters with Supercritical Compressible Flow," Trans. ASME, Vol. 73, July 1951, p. 625.

7 Buckingham, E., "Notes on Contraction Coefficients of Jets of Gas," *Journal of Research,* NBS, Vol. 6, 1931, p. 765.

8 Buckingham, E., "Notes on the Orifice Meter; the Expansion Factor for Gases," *Journal of Research,* NBS, Vol. 9, 1932, p. 61.

9 Perry, J. A., "Critical Flow Through Sharp-Edged Orifices," Trans. ASME, Vol. 71, Oct. 1949, p. 757.

10 Murdock, J. W., and Foltz, C. J., "Experimental Evaluation of Expansion Factors for Steam," Trans. ASME, Vol. 75, July 1953, p. 953.

11 Weisbach, J., *Mechanics of Engineering,* Translated by E. B. Coxe, Van Nostrand, 1872, p. 821. See also Weisbach's *Die Experimental-Hydraulik,* Engelhardt-Freiberg, 1855, p. 133.

12 Benedict, R. P., Carlucci, N. A., and Swetz, S. D., "Flow Losses in Abrupt Enlargements and Contractions," *Journal of Engineering for Power,* Trans. ASME, Series A, Vol. 88, No. 1, Jan. 1966, p. 73.

DISCUSSION

E. F. Brown[2]

The author is to be complimented for presenting a well organized and well written paper. I feel, however, that I may have something to contribute to this paper as a result of a somewhat

[2] Assistant Professor of Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Va.

more theoretical investigation of supercritical orifice flows which I conducted a short time ago.[3] The following facts were revealed during the course of this investigation which have bearing on this paper.

1 The discharge coefficient does not monotonically increase as the pressure ratio is reduced as is predicted by this paper. Rather, a certain value of the pressure ratio R_b is reached less than which the discharge coefficient remains constant. For $\beta = 0.5$ this pressure ratio was calculated in the reference below to be 0.035.

2 The vena contracta does not continue to exist as the pressure ratio is reduced to zero. There is a certain value of the pressure ratio R_b (approximately 0.00029) below which the area of the stream tube expands immediately upon leaving the orifice thus making the definition of C_c impossible.

3 The sonic line does not lie at the vena contracta as assumed here but extends from the orifice lip to a point on the center line approximately 0.5 orifice radii downstream of the orifice depending upon the pressure ratio R_3.

Finally, the calculation of the discharge coefficient in the reference below, which is well within the 2 percent accuracy claimed for the contraction coefficient here, requires only one empirical parameter compared with the two experimental coefficients and numerous assumptions required in this paper.

H. S. Hillbrath[4]

I believe the author to be incorrect in his initial assumption, that is, that it is conventional for any type of head meter to use an expansion factor to relate actual compressible flow rate to the arbitrary flow of an ideal liquid. While this is true at pressure ratios near unity, at lower pressures ratios and especially at supercritical pressure ratios, the nearly universal approach is to use the isentropic, one dimensional approach based on inlet stagnation conditions. This method, including determination of stagnation conditions from static conditions, is discussed in any gas dynamics text (Shapiro[5] for example). If a reference flow is used, it is logically the critical isentropic flow rate.

Flow rate at supercritical pressure ratios, for the types of nozzles and venturis most often used as critical flow meters, does not depend on the pressure differential but only on upstream conditions. The computation of a reference flow based on the irrevelant pressure differential and the elimination of this imaginary effect by an expansion factor introduces unnecessary error and labor. The correct result is obtained directly from the elegantly simple critical flow relations.

It should be noted that the author's Fig. 7 (d) and his confirmation of the theoretical flattening of the curve is equally a confirmation of the well established isentropic, one dimensional gas dynamic analysis of nozzle flows.

Would the author clarify the use of specific weight beginning with equation (18) for compressible flows? Apparently, this requires the use of inlet static temperature which is less commonly used than total temperature.

[3] "Compressible Flow Through Convergent Conical Nozzles With Emphasis on the Transonic Region," PhD thesis, University of Illinois, 1968.

[4] Specialist Engineer in the Thermodynamics and Fluid Systems Technical Staff, The Boeing Co., New Orleans, La. Mem. ASME.

[5] Shapiro, A. H., *The Dynamics and Thermodynamics of Compressible Fluid Flow*, Vol. I, The Ronald Press, New York, 1953.

Author's Closure

I want to thank Professor Brown and Mr. Hillbrath for their interest in this paper. Concerning Dr. Brown's first point, namely that the *theoretical* discharge coefficient attains a constant value at a pressure ratio of about 0.035, Benson and Pool[6] also predict such *theoretical* behavior. For a two-dimensional slit with a β of 0.42 they indicate that the maximum value of the discharge coefficient is reached at an overall pressure ratio of 0.0389. However, in another paper, Benson and Pool[7] report that *experimentally* such behavior was not confirmed. They conclude that the approximations of Jobson's and Bragg's (and hence ours) give entirely satisfactory results. On the second point, while I have not examined the vena contracta characteristic in detail, I feel confident that the pressure ratio of 0.00029, whereupon the vena contracta ceases to exist, is not encountered routinely. Dr. Brown's point three is well taken. Jobson[8] has illustrated the sonic locus as described, but such refinements are considered beyond the scope of the one-dimensional analysis presented here. Finally, it is gratifying to learn that the comparison between the more theoretical analysis of Dr. Brown and the approximate coefficients of this paper agree so well. It would have been helpful if such comparisons were presented graphically in the discussion.

Mr. Hillbrath is well aware that the Fluid Meters Research Committee [1] recommends the use of the expansion factor for flow rate determinations. This is the basis of our statement that such usage is conventional. Of course there are other ways to meter flow, and it is recognized that the use of critical flow nozzles and venturis is popular. However, I am of the opinion that authoritative discharge coefficients are not available for use with such fluid meters. I know that such coefficients are not published in the ASME Report [1]. Mr. Hillbrath also is quite familiar with our work in gas dynamics and our use of the isentropic critical flow rate for reference purposes,[9] but the main objective of this present paper is to make available a generalized expansion factor for *any opening*, for use by those who would still determine flows by the conventional method. As to the use of specific weight in many of the equations, it is quite correct that this quantity is a function of the static temperature. There are several reasons for this usage. First, continuity is written in terms of static conditions so that specific weight naturally is introduced in the flow equations. To obtain the static temperature from the total temperature at inlet one simply applies the elementary isentropic relation

$$\frac{T_1}{T_{t1}} = \left(\frac{P_1}{P_{t1}}\right)^{\frac{\gamma-1}{\gamma}}$$

Second, some beneficial cancelling of specific weight can be made in such expressions as the expansion factor which ratios compressible and incompressible flow rates.

The author again wishes to thank both discussers for contributing their different viewpoints on the subject matter presented here.

[6] Benson, R. S., and Pool, D. E., "Compressible Flow through a Two-Dimensional Slit," *International Journal of Mechanical Science*, Vol. 7, 1965, p. 315.

[7] Benson, R. S., and Pool, D. E., "The Compressible Flow Discharge Coefficients for a Two-Dimensional Slit," *International Journal of Mechanical Science*, Vol. 7, 1965, p. 337.

[8] Jobson, D. A., "On the Flow of a Compressible Fluid through Orifices," *Proceedings of the Institute of Mechanical Engineers*, Vol. 169, No. 73, 1955, p. 767.

[9] Benedict, R. P., and Steltz, W. G., *Handbook of Generalized Gas Dynamics*, Plenum, 1966; Benedict, R. P., and Carlucci, N. A., *Handbook of Specific Losses in Flow Systems*, Plenum, 1967.