DISCUSSION

H. V. Beck[4]

The authors are to be complimented on the preparation of a computation method that is both theoretically sound and very practical.

The method of determining the critical flow function for nonideal gases, presented by the authors, suggests possible means of establishing more accurate performance data on critical flow nozzles used for the measurement of natural gas. These small flow nozzles have been used for the past 30 years in the natural gas industry for the field calibration of displacement type gas meters. While the conventional methods of calculation—assuming the ratio of specific heats to be constant, and to be the exponent for the isentropic expansion—were apparently adequate, the greater accuracy presently required in the natural gas industry would seem to justify a more accurate test procedure.

The properties of gases presently available correspond to the pure substances normally employed in industrial and research operations. Natural gas, however, is a mixture of a number of hydrocarbons with some inerts—principally in the form of carbon dioxide, nitrogen, and oxygen. An evaluation of the thermodynamic properties of such mixtures, and their performance as a composite gas, becomes quite complex. Prof. Wayne C. Edmister in his "Applied Hydrocarbon Thermodynamics" has presented a means of approximating the isentropic exponents for such mixtures. Possibly a combination of Edmister's procedure with the method outlined by the authors could be used to establish the most accurate factors for adapting the critical flow nozzle to natural gas measurements.

During the past year the writer has conducted preliminary tests with weighed air and weighed natural gas of known analysis. Fortunately, for the pressures and temperatures normally encountered in field operations, the results to date indicate a rather close confirmation of the calculated performance from the older methods of computation. It does appear, however, that for more accurate flow measurement, some adjustment should be made for the prevailing Reynolds number and for the actual mean isentropic exponent.

When more complete test information is available it is hoped that the various authorities on this type of measurement could be induced to collectively prepare a calculation procedure that would be quite accurate—but still not be too laborious for a field calibration made at the "fork of the creeks."

W. C. Edmister[5]

The critical flow function, which these authors evaluated by a flow maximization technique, can also be obtained with less computation effort by an exponent technique. This method is illustrated for the same superheated steam point used by Murdock and Bauman to illustrate their procedure.

An isentropic exponent for the change of volume with pressure is required in this alternate calculation. This exponent is defined by the following:

$$n = -\frac{V}{P}\left(\frac{\partial P}{\partial V}\right)_S = \left(\frac{\log P_2 - \log P_1}{\log V_1 - \log V_2}\right)_S \qquad (11)$$

For isentropic paths of the length encountered in critical flow computations, the exponent n is constant and can be evaluated by either the differential or difference relationships given in equation (11).

In terms of this exponent it can be shown that the critical flow function is

$$\phi = \frac{GT^{1/2}}{P} = \sqrt{\frac{g_c T}{PV}}\sqrt{n\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}} \qquad (12)$$

In computing the critical flow function by equation (12) it is not necessary to establish the critical flow pressure precisely. An approximate value of P_{CF} is good enough for predicting the exponent n. This is illustrated in the following recalculation of the example given in Fig. 10 of the authors' paper.

Initial conditions:	P_1 = 4000 psia,	T_1 = 1600 deg F	
	V_1 = 0.2943,	S_1 = 1.6795	
Assumed final:	P_x psia	2000	2300
Isentropic	T_x deg F	1322.5	1374.7
Isentropic	V_x, cu ft/lb	0.5087	0.4553
Exponent n via equation (11)		1.266	1.266

Calculation of Critical Flow Function

$\sqrt{g_c T/PV}$	0.625	0.625
$\sqrt{n\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}}$	0.662	0.662
ϕ	0.4135	0.4135

From the foregoing calculation it can be seen that the same values of ϕ were found at each of the two assumed final pressures because the exponents were the same for each case. Actually only one calculation was necessary, as compared with six and a graph made by the authors.

This method, as well as the authors' method, required comprehensive and precise tabulations of thermodynamic properties. When such compilations are not available, generalized methods for estimating the exponents and compressibility factors may be used.

Robert M. Reimer[6]

This paper is very welcome to the field of high pressure ratio flow measurement. I support the authors' introductory statement about the ASME fluid meter equations.

Of most interest to me is the comparison of equations (1), (2), (6) and Steltz's equation. Fig. 4 illustrates what has been observed in reference [4]; that the flow function for air is constant for any fixed value of inlet enthalpy at pressures below 300 psi. This is nearly true for steam, except for higher pressures, and one should be able to throttle steam from constant reservoir conditions into two critical nozzles in series, and the inlet stagnation pressure ratios of the nozzles should ideally remain constant regardless of the pressure level. This is an ideal and practical way of checking out a flow measuring system before performing serious test work.

The ordinate of Fig. 7 could be considered as ϕ_z/ϕ_h, or equation (6)/equation (2), because ϕ_h is equal or proportional to ϕ_o. It would be interesting to see this ordinate plotted against the wide range of pressure used in the other figures.

Authors' Closure

The authors wish to thank each of the discussers for their contributions to this paper. The comments which follow apply specifically to the discussions.

Mr. H. V. Beck's discussion is most appreciated and strengthens the authors' hope that their paper might be followed by other papers on nonideal gases. The application to natural gas, as stated by Mr. Beck, would be difficult since the thermodynamic properties are yet unavailable.

It is felt that for natural gas, the degree of accuracy presented

[4] Vice-President and Chief Engineer, American Meter Co., Philadelphia, Pa. Mem. ASME.

[5] Professor, Oklahoma State University, Stillwater, Okla. Mem. ASME.

[6] Consulting Engineer, Advanced Engine & Technology Department, General Electric Company, Cincinnati, Ohio. Mem. ASME.

by the critical flow function would not be necessary. An exponent technique such as that presented by Professor Edmister in his "Applied Hydrocarbon Thermodynamics" would undoubtedly be more practical.

When thermodynamic properties are available for natural gas, it would be possible to establish an equation such as equation (8) for accurate field calculations for natural gas flow rates. In fact, a simple graph or table of values, such as Table 2, could easily be used in the field.

Prof. W. C. Edmister's discussion again introduces the exponent technique. The authors wish to say that this is indeed an approach to the problem; however, the approach taken in this paper was to utilize a method that avoided any use of ideal gas, specific heat ratios, or their equivalents.

The method of flow maximization, as noted by Prof. Edmister, is quite time consuming and requires many trials to arrive at a maximum; however, the calculations are now completed. The values are tabulated and the work involved in arriving at the critical flow function requires only a table to look up and possibly a simple interpolation. No estimated or constant exponents are utilized.

Mr. Robert M. Reimer's discussion points out the basic similarities presented by his paper reference [4], this paper, and the information presented by Steltz, reference [7], stresses the non-dependence of the functions on pressure, but rather the strong dependence on the energy level of the inlet state.

A similar plot would result if a plot of ϕ_z/ϕ_o versus reduced inlet temperature was made. The dimensionless correlation on reduced coordinates was only shown for future work and was therefore not pursued further. The pressure range shown was not as wide as the other plot to prevent crowding.

The discussions stimulated by this paper indicate the interest and need for further writings in this area. Extensions to the concepts introduced here would be most useful.