THE ORIFICE EXPANSION CORRECTION FOR A 50 MM LINE SIZE AT VARIOUS DIAMETER RATIOS

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ABSTRACT

The expansion coefficient or factor for a compressible flowmeter corrects for the change in pressure and density as the fluid is accelerated through the flowmeter. The expansion correction currently in use in the United States and also in other countries was developed over fifty years ago by Buckingham[1] and Bean.[2] More recent work reported by Kinghorn[3] shows the equation currently in use to be in error.

This paper describes the results of a test program to determine the expansion factors for flange-tapped sharp-edged orifices with diameter ratios between 0.242 and 0.726 in a nominal 50 mm (2 inch) line. Critical flow Venturis are used as the reference standards and dry air as the flowing fluid. The ratio of differential pressure to inlet static pressure is varied over a range of zero to about 0.2 at a constant Reynolds number. The expansion factor is determined from the apparent change in discharge coefficient at a constant Reynolds number.

SYMBOLS

Symbol	Quantity	Units
C	Discharge coefficient	dim
C_{ref}	Reference discharge coefficient	dim
d	Orifice bore diameter	m
D	Orifice inlet (pipe) diameter	m
q_m	Mass flowrate	kg/s
x	Pressure ratio, $\Delta p/p_1$	dim
p_1	Static pressure at upstream orifice tap	Pa
x/κ	Acoustic ratio	dim
Δp	Orifice differential pressure	Pa
β	Orifice diameter ratio, d/D	dim
ε_1	Expansion factor based on upstream conditions	dim
κ	Isentropic exponent	dim
ρ_1	Gas density at inlet orifice tap	kg/m^3

INTRODUCTION

It has long been known that the density changes as a compressible fluid flows through a restriction such as an orifice. Using a density calculated based on pressure and temperature measurements made at the inlet or exit plane of the orifice will result in unacceptable errors during the calculation of flowrate.

In the case of Venturis and flow nozzles the expansion which accompanies the change in pressure is in the axial direction only, the expanding gas being contained by the walls of the flowmeter. In the case of the thin plate orifice there are no walls to contain the expansion which therefore takes place radially as well as axially. An empirical equation based on test data is required to correct for the effects of expansion. The variables known to affect the expansion factor are β, κ, and $\Delta p/p_1$.

A general equation of flow used for calculating flow through the orifice flowmeter is:

$$q_m = \frac{\pi}{4} C \varepsilon_1 d^2 \sqrt{\frac{2 \Delta p \rho_1}{1-\beta^4}} \qquad [1]$$

Buckingham[1] and Bean[2] published research on the flow of gas through orifices which led to the development of the following empirical equation to correct for the expansion of gas flowing through an orifice with flange taps:

$$\varepsilon_1 = 1 - (0.41 + 0.35\beta^4)\frac{\Delta p}{\kappa p_1} \qquad [2]$$

Kinghorn[3] reported on results of the EEC orifice tests which showed that the coefficients in equation [2] were in error by as much as 0.5 percent at $\varepsilon = 0.95$.

EXPERIMENTAL WORK

Test Plan

Much of the experimental expansion factor data has been obtained by establishing an incompressible discharge coefficient using water in one facility and then taking compressible flow data in a gas facility. By rearranging equation [1], setting C equal to C_{ref} which is the discharge coefficient using water, the expansion factor may be calculated:

$$\varepsilon_1 = \frac{4 q_m}{\pi C_{ref} d^2} \sqrt{\frac{1-\beta^4}{2 \rho_1 \Delta p}} \qquad [3]$$

This method has the disadvantage that any bias between the water and gas flow facilities may influence the result.

For this reason it was decided to use a single reference flowmeter to hold the flowrate and Reynolds number constant while the acoustic ratio was varied over a range where expansion effects varied from insignificant to substantial. The reference Cd is established by extrapolating the data back to where the acoustic ratio is zero. This method has the additional benefit that since the Reynolds number is held constant, variations in discharge coefficient are eliminated.

The limits of this test program were to test orifices in a nominal 50 mm line size with diameter ratios of from 0.242 to 0.726. The desired range of $\Delta p/p_1\kappa$ was from close to zero to about 0.2.

Test Setup

The test data was obtained in one of the low flowrate secondary test rigs at Colorado Engineering Experiment Station, Inc. (CEESI).

All data were taken with the orifice run installed downstream of a calibrated critical flow Venturi (CFV). Inlet pressure and temperature to the CFV were controlled in order to maintain a constant mass flowrate and Reynolds number. A heat exchanger was installed upstream of the orifice run to keep variations in temperature, and therefore Reynolds number, to a minimum.

The orifice run had an inlet diameter of 52.48 mm (2.066 in.), an upstream length of 20.3 diameters and a downstream length of 8.7 diameters. An additional 65.6 diameters of pipe were installed upstream of the orifice run and an additional 15 diameters were installed downstream. Since only flange taps were available, data for other tappings were not taken. The orifice plates were aligned with the run by using a micrometer.

A valve was installed downstream of the orifice run to allow the value of $\Delta p/p_1$ to be varied over the desired range.

Instrumentation

Because the flowrate was held constant, the main contributors to experimental uncertainty were the measurement of static pressure and differential pressure. Static pressures were measured with a quartz pressure gauge with an uncertainty of ±(0.01% of reading + 0.002 % of full span). Differential pressures were measured with two "smart" transducers. 'Smart" transducers are internally compensated for changes in ambient temperature and static line pressure. Differential pressure transducers from two different manufacturers were used and the results were averaged. The uncertainty in the differential pressure measurements is estimated to be ± 0.1 percent of reading.

Temperatures were measured with type T thermocouples with an estimated uncertainty of ± 0.1 deg C.

All instruments had current calibrations with traceability to the National Institute for Standards and Technology (NIST).

Fluid Properties

Surface fits of real-gas properties for compressibility and isentropic exponent were used in all calculations.

RESULTS

The results of the tests are presented in tabular form in Tables 1 through 6.

The isentropic exponent was calculated using a surface fit of data from a recent equation of state for air[4]:

$$\kappa = 1.406911 + 1.101435E^{-4}P + 1.599554E^{-7}P^2 \\ -(1.287566E^{-5} + 3.79319E^{-8}P + 2.33454E^{-10}P^2)T \qquad [4]$$

Where T is in degrees R and P is in psia.

The ISO expansion factor was calculated by[6]:

$$\varepsilon = 1 - (0.41 + 0.35\beta^4)\Delta p/\kappa p_1 \qquad [5]$$

When the slope of the discharge coefficient/Reynolds number equation[5] at the test Reynolds number was multiplied by the variation in Reynolds number for each test, the worst case variation in discharge coefficient was 0.0034 percent, an insignificant value.

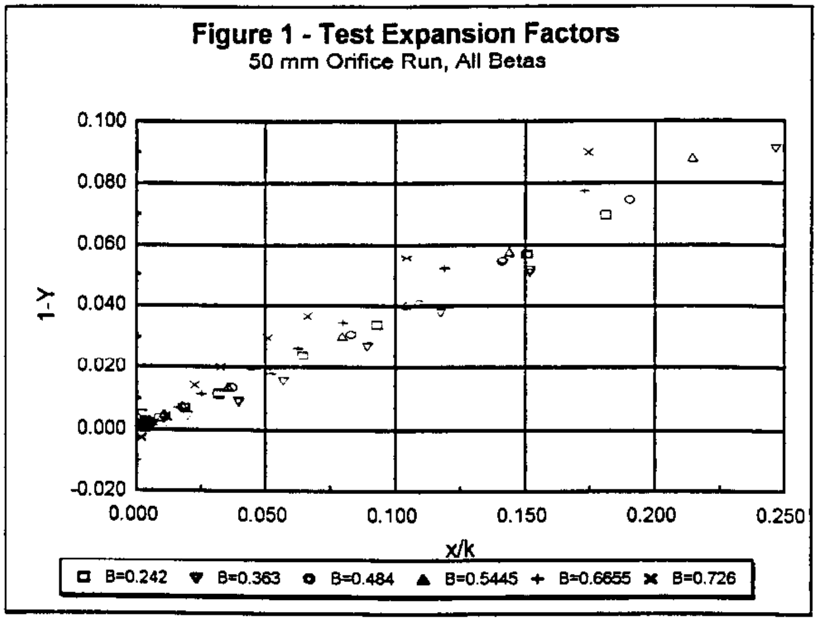
The test expansion factors were calculated using equation [3]. The value of C_{REF} for each orifice was obtained by calculating an incompressible discharge coefficient (with no expansion correction) and then extrapolating to $x/\kappa = 0$.

The percent deviation between the ISO expansion factor (equation [2]) and the test expansion factor was calculated by:

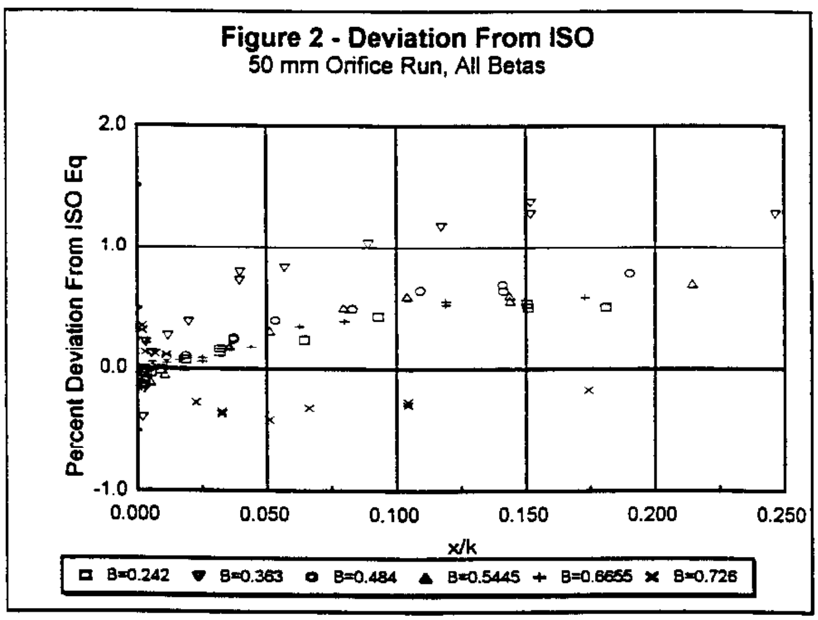
$$\frac{\varepsilon_{TEST} - \varepsilon_{ISO}}{\varepsilon_{ISO}} \, x \, 100\,\% \qquad [6]$$

ANALYSIS OF RESULTS

The data for all values of β are shown as $1 - \varepsilon$ as a function of x/κ in Figure 1.



The deviations of the test expansion factors from the ISO expansion factors is shown graphically in Figure 2.



The deviations are similar to those reported by Kinghorn [3] with the exception of the $\beta = 0.363$ and $\beta = 0.726$ data which shows substantially more deviation. Careful examination of the data revealed no cause for this anomaly; no changes were made in the test setup or instrumentation, only the orifice plate was changed. There was insufficient time to verify the data before completion of this paper but the tests will be rerun at a later date.

One possible cause of this behavior could be the fact that for a 50 mm orifice with flange taps, the vena contracta moves past the downstream orifice tap as the diameter ratio is varied over the range of 0.2 to 0.75. This is due to the fact that geometric similarity is not maintained when the distance from the orifice face to the pressure tap is fixed.

In order to compare this data with the EEC data reported by Kinghorn[3], a similar analysis was performed on the data. Equation [2] was written in the form:

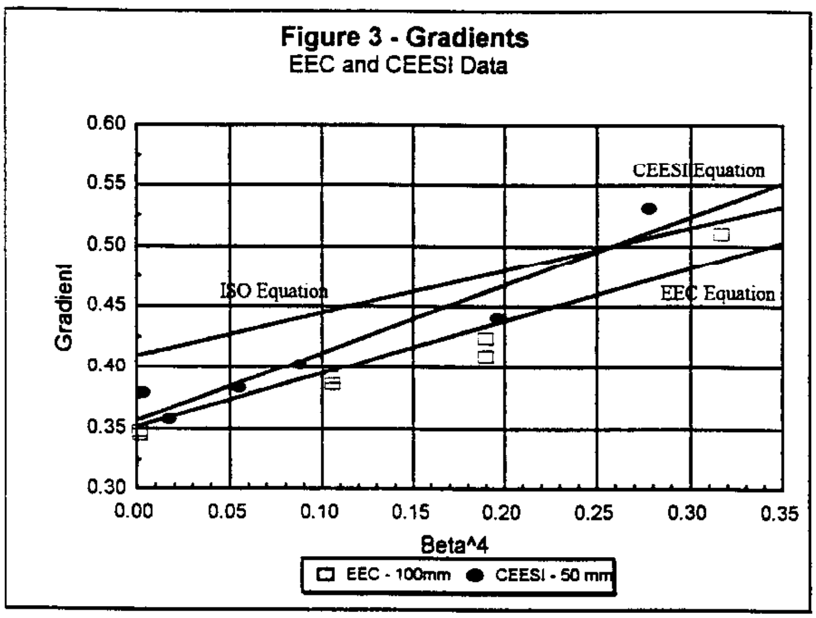
$$1 - \varepsilon = \phi(\beta)\frac{\Delta p}{\kappa p_1} \qquad [7]$$

Slope and intercept values of least-squares straight line fits of the function ϕ are tabulated in Table 7.

A least-squares straight line was fit to the "b" coefficients from Table 7 resulting in the following equation:

$$1 - \varepsilon = (0.357 + 0.557\beta^4)\frac{\Delta p}{\kappa p_1} \qquad [8]$$

The slope values are shown graphically in Figure 3 along with equation [2], equation [8], and equation [10] from Kinghorn.[3]



The CEESI and EEC data predict a lower intercept (Beta = 0) value than the ISO equation and the CEESI data predicts a steeper slope of the expansion factor. If the B = 0.726 data is excluded from the CEESI equation then the slope of the CEESI equation is not so steep.

CONCLUSIONS

The CEESI data shows, as did the EEC data, that the current expansion factor equation [2] does not sufficiently represent recent expansion factor data.

There are some differences between the EEC data and the CEESI data which will require further investigation to determine if the differences are due to orifice meter run diameter or other causes.

Additional data should be gathered on different line sizes, a variety of diameter ratios, and on multiple plates with the same bore. A new equation should be proposed from a qualified data base. To improve accuracy, the new equation should be of a form to take into account the non-linearity of the expansion factor as a function of acoustic ratio.

Errors in the current expansion factor have been propagated to the discharge coefficient versus Reynolds number relationships used to formulate the current code equations.

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Table 1 Orifice 1A B = 0.2420

Pt	DP kPa	P1 Static P kPa abs	T1 Temp, deg K	Mass flowrate kg/sec	Ratio x/k dim	Test Exp Fac dim	ISO Exp Fac dim	% Dev %
1	7.1583	2130.9	293.49	0.045963	0.00235	0.99901	0.99904	-0.00
2	8.4845	1801.7	293.32	0.045976	0.00330	0.99838	0.99864	-0.03
3	10.578	1449.8	293.26	0.045994	0.00514	0.99757	0.99789	-0.03
4	8.5086	1800.6	293.46	0.046008	0.00331	0.99819	0.99864	-0.04
5	13.959	1103.7	293.19	0.046021	0.00894	0.99624	0.99633	-0.01
6	20.328	763.73	293.08	0.046031	0.01887	0.99299	0.99224	0.08
7	26.520	591.39	293.02	0.046035	0.03185	0.98825	0.98690	0.14
8	38.241	420.85	292.96	0.046040	0.06464	0.97587	0.97342	0.25
9	26.528	591.56	293.23	0.046049	0.03185	0.98860	0.98690	0.17
10	46.364	354.68	293.00	0.046058	0.09305	0.96597	0.96174	0.44
11	60.376	285.81	292.95	0.046067	0.15047	0.94320	0.93813	0.54
12	67.141	264.21	292.89	0.046071	0.18105	0.93030	0.92555	0.51
13	60.508	285.48	292.89	0.046071	0.15097	0.94270	0.93792	0.51

Table 2 Orifice 2A B = 0.3630

Pt	DP kPa	P1 Static P kPa abs	T1 Temp, deg K	Mass flowrate kg/sec	Ratio x/k dim	Test Exp Fac dim	ISO Exp Fac dim	% Dev %
1	5.3424	1795.4	292.37	0.083946	0.00209	0.99518	0.99913	-0.40
2	6.6486	1450.0	292.29	0.084291	0.00323	0.99711	0.99866	-0.15
3	8.7375	1105.2	292.22	0.084477	0.00558	0.99887	0.99768	0.12
4	6.6579	1447.7	292.43	0.084586	0.00324	1.00094	0.99865	0.23
5	12.734	764.63	292.04	0.084717	0.01181	0.99785	0.99509	0.28
6	16.569	591.65	291.97	0.084799	0.01989	0.99561	0.99173	0.39
7	23.506	422.21	291.89	0.084881	0.03960	0.99065	0.98352	0.72
8	28.404	354.49	291.78	0.084962	0.05703	0.98438	0.97627	0.83
9	23.536	422.21	291.72	0.085017	0.03965	0.99130	0.98350	0.79
10	36.013	286.76	291.61	0.085044	0.08945	0.97277	0.96278	1.04
11	41.755	252.91	291.55	0.085071	0.11763	0.96224	0.95106	1.18
12	48.160	225.84	291.49	0.085126	0.15198	0.94871	0.93676	1.27
13	64.087	185.22	291.32	0.085207	0.24669	0.90880	0.89736	1.28
14	48.156	225.84	291.27	0.085235	0.15197	0.94960	0.93677	1.37

Table 3 Orifice 3A B = 0.4840

Pt	DP kPa	P1 Static P kPa abs	T1 Temp, deg K	Mass flowrate kg/sec	Ratio x/k dim	Test Exp Fac dim	ISO Exp Fac dim	% Dev %
1	5.1951	1789.3	290.67	0.148601	0.00204	0.99790	0.99913	-0.12
2	6.4211	1444.3	290.35	0.148424	0.00313	0.99784	0.99866	-0.08
3	8.3993	1101.9	290.18	0.148211	0.00538	0.99772	0.99769	0.00
4	6.3871	1444.3	290.29	0.147971	0.00311	0.99733	0.99866	-0.13
5	12.128	761.25	290.02	0.147730	0.01129	0.99603	0.99515	0.09
6	15.654	591.69	289.91	0.147504	0.01879	0.99299	0.99194	0.11
7	22.175	422.25	289.85	0.147313	0.03736	0.98655	0.98397	0.26
8	26.646	354.53	289.74	0.147141	0.05350	0.98100	0.97704	0.41
9	22.058	422.25	289.80	0.146937	0.03716	0.98655	0.98405	0.25
10	33.564	286.80	289.69	0.146714	0.08335	0.96903	0.96422	0.50
11	38.799	252.95	289.64	0.146651	0.10928	0.95927	0.95310	0.65
12	44.732	225.88	289.47	0.146764	0.14113	0.94593	0.93943	0.69
13	53.118	198.80	289.31	0.146823	0.19046	0.92543	0.91825	0.78
14	44.831	225.88	289.30	0.146873	0.14144	0.94530	0.93929	0.64

Table 4 Orifice 4A B = 0.5445

Pt	DP kPa	P1 Static P kPa abs	T1 Temp, deg K	Mass flowrate kg/sec	Ratio x/k dim	Test Exp Fac dim	ISO Exp Fac dim	% Dev %
1	4.8227	1789.9	292.22	0.184567	0.00189	0.99911	0.99917	-0.01
2	6.0068	1445.0	292.35	0.184735	0.00293	0.99800	0.99871	-0.07
3	7.9091	1102.5	292.33	0.184830	0.00507	0.99672	0.99777	-0.10
4	6.0163	1445.0	292.43	0.184925	0.00293	0.99840	0.99871	-0.03
5	11.514	762.01	292.15	0.185002	0.01071	0.99484	0.99528	-0.04
6	14.906	592.39	292.03	0.185097	0.01787	0.99226	0.99212	0.01
7	21.155	422.95	291.86	0.185170	0.03558	0.98612	0.98432	0.18
8	25.482	355.22	291.74	0.185229	0.05106	0.98066	0.97749	0.32
9	21.173	422.95	291.68	0.185324	0.03561	0.98624	0.98430	0.20
10	32.237	287.50	291.45	0.185401	0.07986	0.96970	0.96480	0.51
11	37.161	253.65	291.28	0.185097	0.10438	0.95974	0.95399	0.60
12	44.374	219.80	291.17	0.184812	0.14388	0.94191	0.93658	0.57
13	55.936	185.96	290.96	0.184812	0.21445	0.91182	0.90547	0.70
14	44.338	219.80	291.01	0.184866	0.14377	0.94230	0.93663	0.61

Table 5 Orifice 5A B = 0.6655

Pt	DP kPa	P1 Static P kPa abs	T1 Temp, deg K	Mass flowrate kg/sec	Ratio x/k dim	Test Exp Fac dim	ISO Exp Fac dim	% Dev %
1	1.9721	1444.9	291.47	0.170637	0.00096	0.99916	0.99954	-0.04
2	2.5921	1102.4	291.36	0.170723	0.00166	0.99859	0.99920	-0.06
3	3.7411	761.9	291.18	0.170796	0.00348	1.00057	0.99833	0.22
4	2.5984	1102.4	291.28	0.170846	0.00167	0.99797	0.99920	-0.12
5	4.8476	592.3	291.01	0.170932	0.00581	0.99774	0.99722	0.05
6	6.8344	422.8	290.90	0.170986	0.01150	0.99494	0.99450	0.04
7	8.1705	355.1	290.83	0.170968	0.01638	0.99287	0.99216	0.07
8	10.1972	287.4	290.71	0.171072	0.02527	0.98846	0.98790	0.06
9	13.5663	219.7	290.53	0.171213	0.04401	0.98079	0.97893	0.19
10	10.2167	287.4	290.53	0.171335	0.02532	0.98872	0.98788	0.09
11	16.3114	185.8	290.32	0.171440	0.06258	0.97350	0.97005	0.36
12	18.6374	165.5	290.15	0.171530	0.08031	0.96539	0.96156	0.40
13	23.1239	138.3	289.97	0.171585	0.11923	0.94795	0.94293	0.53
14	28.6177	118.0	289.64	0.171653.	0.17304	0.92258	0.91717	0.59
15	23.1173	138.3	289.70	0.171689	0.11919	0.94822	0.94295	0.56

Table 6 Orifice 6A B = 0.7260

Pt	DP kPa	P1 Static P kPa abs	T1 Temp, deg K	Mass flowrate kg/sec	Ratio x/k dim	Test Exp Fac dim	ISO Exp Fac dim	% Dev %
1	3.1497	1789.7	290.06	0.305068	0.00123	0.99767	0.99937	-0.17
2	3.8581	1444.8	289.40	0.305068	0.00188	1.00264	0.99905	0.36
3	5.0759	1102.4	289.17	0.304705	0.00325	0.99970	0.99835	0.14
4	3.8426	1444.8	289.28	0.304415	0.00187	1.00231	0.99905	0.33
5	7.3413	761.8	288.95	0.303957	0.00683	0.99776	0.99653	0.12
6	9.4735	592.2	288.84	0.303666	0.01136	0.99536	0.99424	0.11
7	13.5355	422.8	288.66	0.303730	0.02277	0.98578	0.98845	-0.27
8	16.3094	355.1	288.49	0.303793	0.03269	0.98001	0.98342	-0.35
9	20.5553	287.3	288.21	0.303825	0.05095	0.97015	0.97415	-0.41
10	16.3101	355.1	288.28	0.303861	0.03270	0.97985	0.98341	-0.36
11	23.6234	253.5	287.87	0.303925	0.06640	0.96330	0.96632	-0.31
12	30.1973	206.1	287.53	0.303957	0.10443	0.94452	0.94703	-0.26
13	40.4643	165.4	286.90	0.304020	0.17441	0.90999	0.91153	-0.17
14	30.1979	206.1	287.21	0.304057	0.10443	0.94428	0.94702	-0.29

Table 7 Values Of Coefficients For Equation 7

Orifice	Beta	a coef	b coef
1A	0.2420	0.0000	0.3791
2A	0.3630	-0.0022	0.3577
3A	0.4840	0.0000	0.3833
4A	0.5445	0.0000	0.4025
5A	0.6655	-0.0001	0.4407
6A	0.7260	0.0000	0.5310