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PERFORMANCE OF DIVERTERS UNDER MULTI-PHASE FLOW

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Objective: To enhance design criteria for blowout prevention systems used to handle shallow gas.

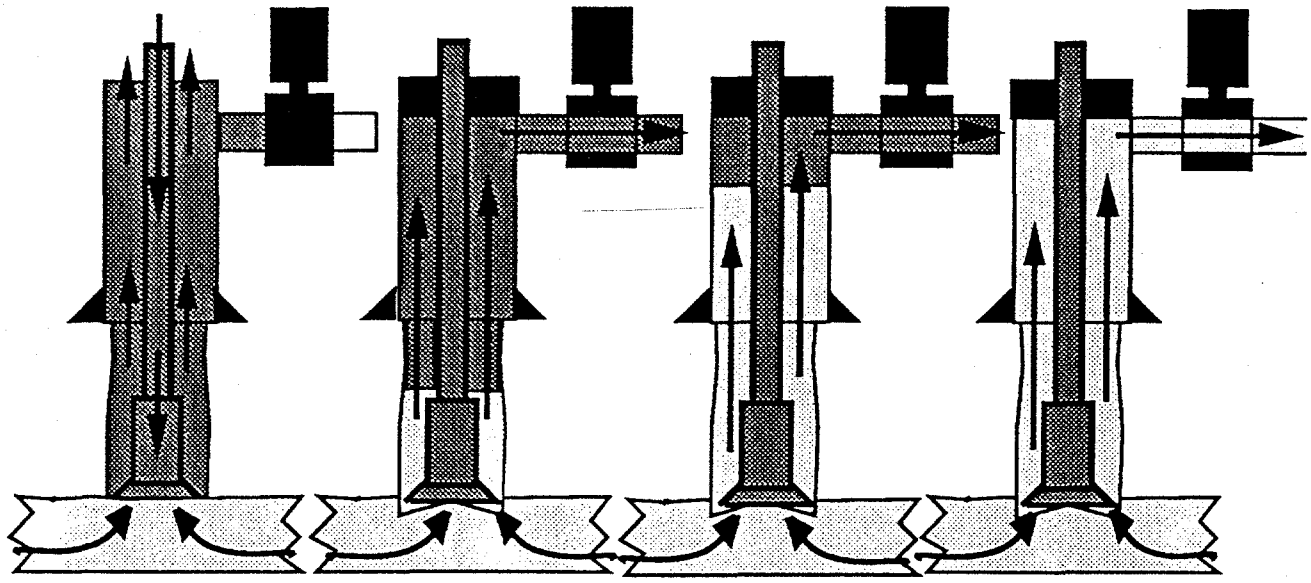
Introduction

Safety of personnel, equipment and environment is a concern in offshore hydrocarbons explorations. Blowouts are among the most dangerous hazards in marine environments where abnormal formation pressures may be encountered at very shallow depths. Well control is especially difficult where a threatened blowout situation occurs prior to setting surface casing in the well. If the conventional blowout prevention equipment and procedures are applied, hydraulic fracturing is likely to occur in an exposed shallow formation due to the pressure build-up in the well. Moreover, if one or more fractures reach the surface, the resulting flow can destroy the foundations of a bottom supported structure.

Presently, the best available procedure for handling a threatened blowout from a shallow gas formation is to divert the gas flow away from the rig structure and drilling personnel. This requires the use of a diverter system large enough to prevent a pressure build-up within the well bore, minimizing exposure of the weakest formation to fracture. The essential elements of a diverter system include (1) a vent line for conducting the flow away from the structure, (2) means for closing the well annulus above the vent line during diverter operations, and (3) means for closing the vent line during normal drilling operations.

The sequence of events occurring when a shallow gas flow is encountered are illustrated in Figure 1. When the driller recognizes that the well has begun to flow, the diverter system is actuated (1b). This simultaneously causes the vent line to open and the annular diverter head to close. As drilling fluid is displaced from the well, the rate of gas flow into the well increases due to the loss in bottom-hole pressure (1c). After the well is unloaded of drilling fluid, a semi-steady state condition is reached (1d) in which formation gas, water, and sand are flowing through the vent line.

Although conceptually simple, the design, maintenance, and operation of an effective diverter system for the various types of drilling vessels is a difficult problem. Past experience has shown that when a situation calling for the use of a diverter arises, failure in the diverter system often occurs. Among other factors, failures generally result from higher pressures than expected. The trend to larger pipe sizes in modern diverter systems has reduced the risk of high pressures due to plugging.



(a) Normal flow path (b) Diverter system activated (c) Unloading the well (d) Pseudo-steady state flow

Figure 1 - Events in diverter system operations.

Experimental Equipment and Procedure

This work focused on improving the prediction of diverter line pressure loading due to multiphase flow. The approach taken was to obtain experimental data. Data collection was divided in two parts:

1. Measurement of sonic exit pressures and flowing pressure gradients in the diverter line as a function of low rate for steady state multiphase flow of gas/liquid mixtures (Figure 1d).

2. Measurement of sonic exit pressures and flowing pressure gradients for unsteady state multiphase flow.

A number of model diverter systems were constructed at the LSU/MMS Research Well Facility in order to perform these experiments. Schematic of two models used in this work are shown in Figures 2.and 3.

The model depicted in Figure 2 included a large tank to store high pressured air. The 30 bbl. capacity tank provided the high air flow rates required to reach sonic velocity in the large diameter pipes used in the test section.The test section consisted of around 20 ft. of schedule 40 pipe. Both 8-in. and 10-in. nominal diameter pipes were used. A Tee between the ball valve and the test section was installed to provide an input for the liquid phase. A remote operated ball valve allowed to control the air flow from the tank.

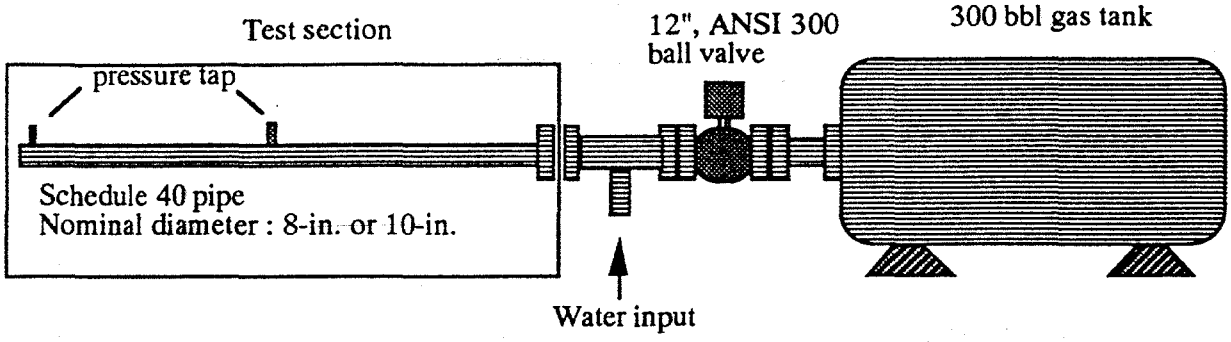


Figure 2 - Schematic of model diverter system for sonic multiphase flow tests in large diameter pipes.

The fluids used in this equipment were tap water and air. Air compressed up to 160 psig was used for all the runs. Water was provided by centrifugal pumps.

The procedure to run the test consisted of (1) start the data acquisition system to capture information such as gas tank pressure, gas tank temperature, liquid flow rate, the exit pressure at the diverter exit ,and the pressure at 10 ft. upstream of the diverter exit.

The model depicted in Figure 3 is representative of the set-up for low gas flow rates required to reach sonic velocity in small diameter pipes. A test section of 40 ft. was used for 4-in. nominal diameter pipe. Natural gas routed through a metering station was used for all the runs. Water was provided by a triplex pump.

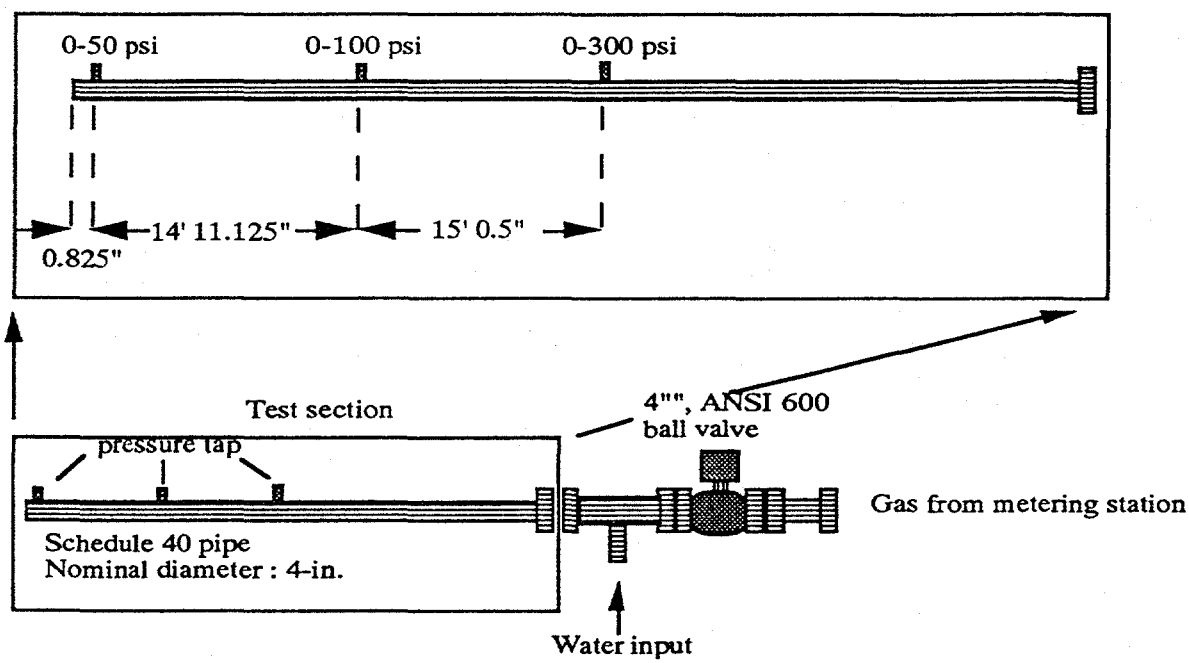


Figure 3 - Schematic of model diverter system for sonic multiphase flow tests in small diameter pipes.

Summary

The experimental data obtained provided valuable insight into the controlling fluid dynamics mechanisms involved in the complex multiphase flow behaviour of well/diverter systems at sonic and near sonic velocities. In the past, backpressure estimated were often made by assuming that the pressure in the diverter exit was atmospheric and the fluid acceleration term was negligible. The experimental data showed that these assumptions could result in large errors.

Beck, Langlinais, and Bourgoyne (1986) have shown that the flow at the vent line exit is usually sonic, and the assumption of atmospheric pressure at the diverter exit can lead to large errors. They also showed that near the exit, a significant pressure gradient resulted from fluid acceleration, which could also cause significant errors if ignored. Experimental data was obtained in a model diverter system to permit evaluation of various methods for calculating flowing pressures for single and multiphase flow at near sonic conditions. Moreover, this error is augmented when fluid acceleration is not accounted for in the calculation of pressure gradients.

Sonic Exit Velocity Calculation

The limiting (sonic) velocity at the diverter vent line exit can be computed for any fluid using

$$v_e = \frac{1}{\sqrt{\rho c}} \qquad \text{. . . . . .} \quad (1)$$

where ρ is the density of the fluid and c is the compressibility of the fluid. For liquids, the density, ρ_l , and compressibility, c_l, can be assumed constant and are easily defined. However, for gases, the density can be determined from the real-gas equation

$$\rho_g = \frac{p\,\overline{M}}{z\,R\,T} \qquad \text{. . . . . .} \quad (2)$$

for any given pressure, p, gas molecular weight, M, gas deviation factor, z, and temperature, T. The coefficient, R, is the universal gas constant for the system of units being used. For most accurate results, the gas compressibility should be computed assuming a polytropic process. This assumption gives

$$c_g = \frac{1}{n\,p} \qquad \text{. . . . . .} \quad (3)$$

where n is the polytropic expansion coefficient for the process. For an adiabatic expansion of an ideal gas, n becomes equal to the ratio, k, of specific heat at constant pressure, C_p, to specific heat at constant volume, C_v . For sonic flow through a restriction, k is often used an an approximate value for n.

When the fluid being produced from the well is a multiphase mixture, Eqn.1 can still be applied through use of appropriate values for effective density and effective compressibility.

The effective multiphase density, ρ_e can be calculated using

$$\rho_e = \lambda_g \rho_g + \lambda_l \rho_l + \lambda_s \rho_s \qquad (4)$$

where λ denotes the volume fraction (hold-up) and subscripts g, 1, and s denotes the gas, liquid, and solid phases present. For sonic flow, the slip velocity between the phases can be neglected when calculating volume fractions. Wallis (1969) recommended calculating an effective compressibility, c, in a similar manner using.

$$c_e = \lambda_g c_g + \lambda_l c_l + \lambda_s c_s \qquad (5)$$

Beck, Langlinais, and Bourgoyne (1987) performed experiments in model diverted systems to measure sonic exit velocities for a natural gas having a specific gravity of 0.64. Data were presented for single and multiphase flow for diverter vent line diameters of 0.0233-m (0.918-in.), 0.0492-m (1.937-in.), and 0.1244-m (4.897-in.). These data were used to determine experimental values for the polytropic expansion coefficient, n. Their results have been curve fitted and are shown in Figure 4 . Note that the measured value of n varied with vent line diameter and gas weight percent (quality) for the range of conditions studied and can be approximated by

$$n = 2.8\, d^{0.25}\left[1 + 5.5\, d^{0.5}(1 - \chi_g)^2\right] \qquad (6)$$

where the diameter, d, is expressed in meters, and χ_g is the weight fraction of gas in the mixture. The experimentally determined value of n departed significantly from k, especially for the largest, 5-in, diameter studied.

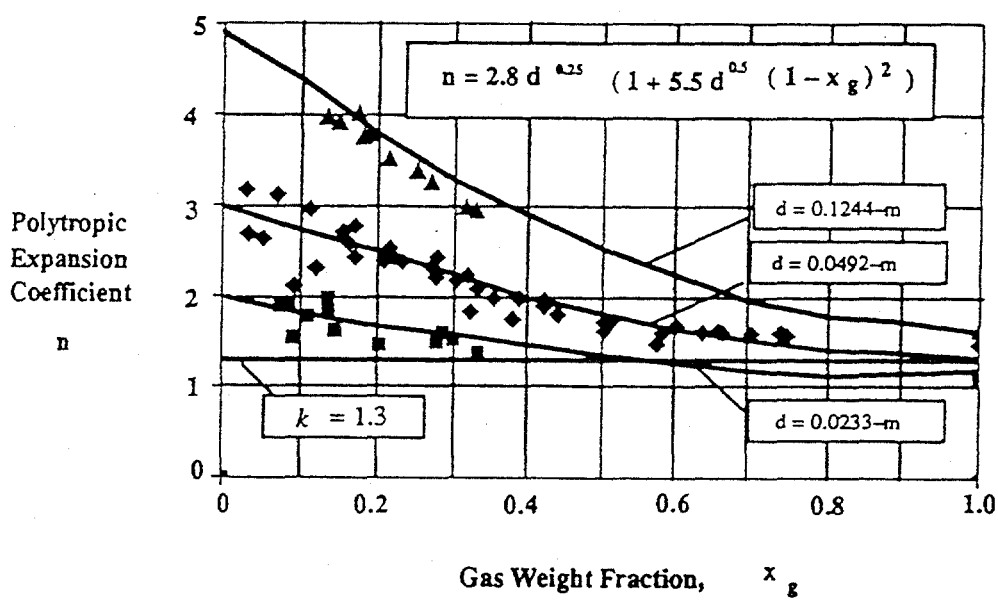


Figure 4 - Polytropic expansion coefficient, n, measured during experimental study of diverter vent line operations for diameters lower than 0.1244-m.

The use of Eqns. 1-6 for calculating the relationship between flow rate and diverter vent line exit pressure is illustrated in Table 1 for a natural gas having a specific gravity of 0.64. It was assumed that no water was produced with the gas, i.e., the gas quality equals 1.0, and that the temperature was 38 °C (100 °F). Calculations were completed for vent line diameter of 0.152-m (6-in.), the previous minimum size approved by the U.S. Minerals Management Service, and for 0.254-m (10-in.) diverter diameter that is now required.

The calculation results given in Table 1 show that a 0.254-m diverter vent line diameter will handle approximately three times the flow rate of a 0.152-m vent line for a given exit pressure. For the smaller line, approximately 10 atmosphere of backpressure would result at the vent line exit for a gas-flow rate of 83 m^3/s, or 250MMScf/D.

Table 1

Example calculation of pressure-flow rate relationship

0.152 m (6-in.) Diverter system vent line exit

Pressure (Pa)	Eqn. 2 Gas density (kg/m^3)	Eqn. 7 Polytropic expansion coefficient	Eqn. 3 Gas compressibility (1/Pa)	Gas volume fraction	Eqn. 1 Exit velocity (m/s)	Flow rate @ S.C (m^3/s)
101 300.	0.728	1.75	5.65×10^{-6}	0.999	493.2	8.34
200 000.	1.441	1.75	2.86×10^{-6}	0.999	492.7	16.48
300 000.	2.167	1.75	1.91×10^{-6}	0.999	492.2	24.75
400 000.	2.896	1.75	1.43×10^{-6}	0.999	491.6	33.05
500 000.	3.629	1.75	1.14×10^{-6}	0.999	491.1	41.37
1000 000.	7.345	1.75	5.72×10^{-6}	0.999	488.5	83.29

0.254 m (10-in.) Diverter system vent line exit

Pressure (Pa)	Eqn. 2 Gas density (kg/m^3)	Eqn. 7 Polytropic expansion coefficient	Eqn. 3 Gas compressibility (1/Pa)	Gas volume fraction	Eqn. 1 Exit velocity (m/s)	Flow rate @ S.C (m^3/s)
101 300.	0.728	1.99	4.97×10^{-6}	0.999	525.9	24.8
200 000.	1.441	1.99	2.51×10^{-6}	0.999	525.3	49.1
300 000.	2.167	1.99	1.68×10^{-6}	0.999	524.8	73.7
400 000.	2.896	1.99	1.26×10^{-6}	0.999	524.2	98.4
500 000.	3.629	1.99	1.01×10^{-6}	0.999	523.7	123.2
1000 000.	7.345	1.99	5.02×10^{-6}	0.999	520.8	248.0

Data acquired for sonic velocities in 7.981-in. and 10.02-in. internal diameter pipes, is displayed in Figure 5. As in the previous Figure 4, the polytropic expansion coefficient is plotted against the gas weight fraction. Disregarding statistical scattering, the data appears indicate decreasing values of coefficient n with increasing values of pipe diameter.

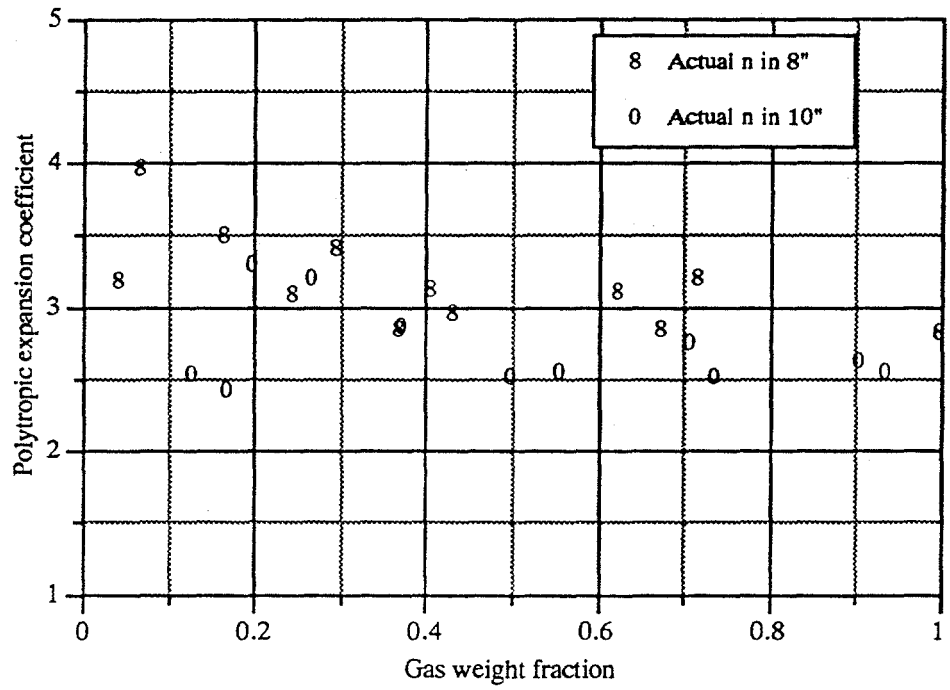


Figure 5 - Polytropic expansion coefficient, n, measured during experimental study of diverter vent line operations for diameters greater than 0.1244-m.

A better comparison is obtained with an overlay of Figures 4 and 5. However this has to be done by plotting a polytropic coefficient group rather than an actual polytropic coefficient so as to eliminate the effect of the gas mass. Note that Figure 4 is for natural gas with a specific gravity of 0.64 whereas Figure 5 is for air. A convenient polytropic expansion coefficient group , N, can be obtained by multiplying the relative polytropic expansion coefficient by the relative gas mass. The relative expansion coefficient is in turn expressed with respect to the specific heat ratio, k, for a given gas. The polytropic expansion group N is given by the following expression

$$N = (n/k)\,(M_g/M) \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (7)$$

Figure 6 exhibits the polytropic coefficient group, N, as a function of the gas mass fraction. This figure indicates the polytropic expansion coefficient number, for the larger pipes, lies between those of 1.937-in(0.0492-m) and 0.917-in(0.0233-m) for gas fractions lower than around 0.8, i.e., there is an inversion on the trend of the coefficient number N; namely N values decrease as the pipe diameters increase. On the other hand, for gas fractions higher than around 0.8, the correlation given as Equation 6 applies, i.e., the coefficient n increases as the pipe diameter increases and so does the group N.

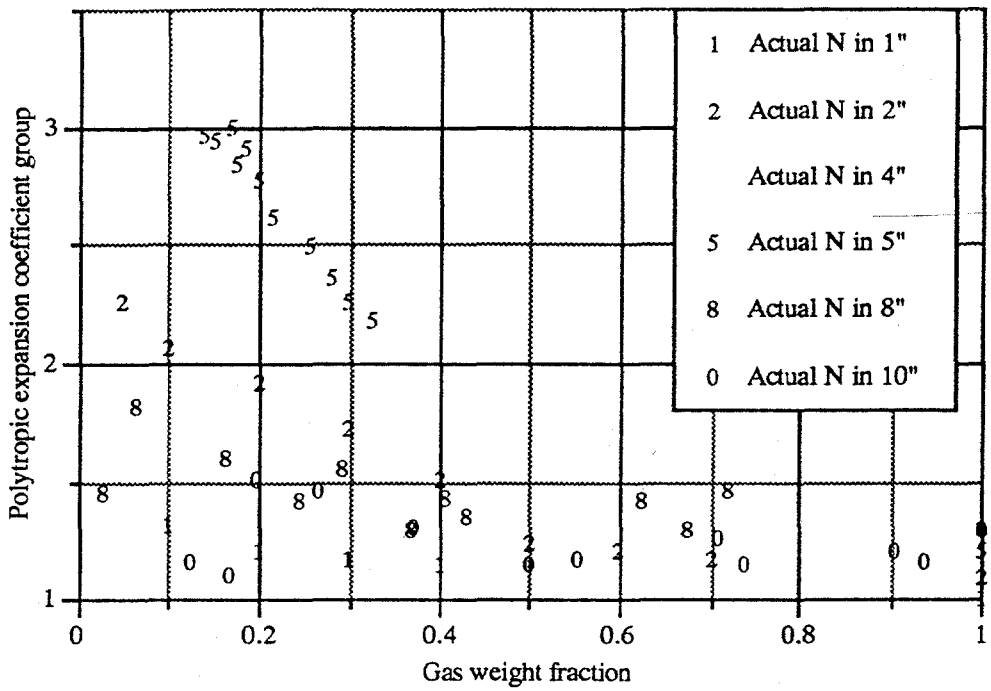


Figure 6 - Polytropic expansion coefficient group,N, as a function of the gas weight fraction for nominal diameters of 1, 2, 5, 8, and 10-in.

Apparently, there is an upper bound up to which the n coefficient increases with diameter. The upper bound appears to be a diameter of around 5-in (0.127-m.). Additional tests, in pipe of 4-in nominal diameter, were run on September 1991. These tests aimed to collect data in a wide range of gas fractions; particularly they focused in acquiring data to cover the gap between 0.32 and 1.00 gas fraction for pipes in the range of 1 to 5-in.(see Figure 6). The results of this tests is shown in Table 2.

The two first columns of Table 2 are the calculated mass gas fraction and the empirical polytropic expansion coefficient. The measured data, used to calculate these parameters, is reported in the last three columns of the table; in fact,column three is the measured gas flow rate, column four is the pressure at the pipe exit, and column six is the measured water flow rate. Eighty degrees Fahrenheit was the average temperature at the exit of the diverter system.

On one hand,these data confirm the discussed trend sugested by Figure 6. As it is shown in Figure 7, the data for 4-in.nominal diameter pipe almost collapses with that of 5-in., and fills the hiatus of data for gas weight fractions in the domain (0.32, 1.0). Moreover the data closely follows the correlation presented as Equation 6,i.e.,the date enhances the trend shown in Figure4. In Figure 7 also it is clearly seen that this correlation holds for pipe diameters below of 6-in., and that the trend reverses for pipes of larger diameters.

Table 2

Polytropic expansion coefficient in diverter system of 4-in. nominal diameter. Fluids: water and natural gas.

Gas weight fraction	Polytropic expansion coefficient	Gas flow rate @ S.C. MMSCFD	Exit pressure psig	Water flow rate Gpm
.3724119	2.815302	20.00	17.00	132.00
.3603254	2.90868	19.05	15.50	132.45
.3804447	2.866942	19.05	14.90	121.50
.3940063	2.824745	19.05	14.60	114.75
.4136674	2.774484	19.05	14.15	105.75
.4511921	2.661528	19.05	13.50	90.75
.4952157	2.549116	19.05	12.80	76.05
.5939762	2.322496	19.05	11.60	51.00
.6610797	2.245477	19.05	10.65	38.25
.8188971	1.988367	19.05	9.50	16.50
.7711944	1.863887	14.20	4.50	16.50
.6495885	2.213413	14.20	4.50	30.00
.4810300	2.701936	14.20	5.50	60.00
.3920217	2.901225	14.20	6.90	86.25
.3087696	3.168489	14.20	8.60	124.50
.2441457	2.655836	12.00	9.50	145.50
.2666622	3.399236	12.20	6.10	131.40
.2912913	3.265712	12.20	5.60	116.25
.3255244	3.101703	12.20	5.00	99.00
.3867922	2.926638	12.20	3.90	75.75
.5051845	2.588583	12.20	2.60	46.80
.4392388	2.241023	9.36	0.60	46.80
.3209757	2.823816	9.36	1.25	77.55
.2696273	3.105232	9.36	1.90	99.30
.2278227	3.348946	9.04	2.10	120.00
.2029450	3.588528	9.04	2.50	139.05

On the other hand, the polytropic expansion group only increases with the diameter for gas qualities larger than 0.9. Moreover the polytropic expansion coefficient group for 8-in. and 10-in. decreases with the increasing diameter , and: (a) it falls between those of 2-in. and 1-in.for gas qualities below 0.6, and (b) it falls between those of 4-in. and 2-in. for gas qualities from 0.6 to 0.9. Moreover, apparently the polytropic group tends to that of the specific heat ratio of the gas as the pipe diameter increases.

Analysis of the dependence of the polytropic expansion coefficient group as a function of pipe diameter requires further discussion; the dependence of the N on the pipe dimeter is better done by plotting the polytopic expansion coefficient group as a function of pipe diameter as it is shown in Figure 8.

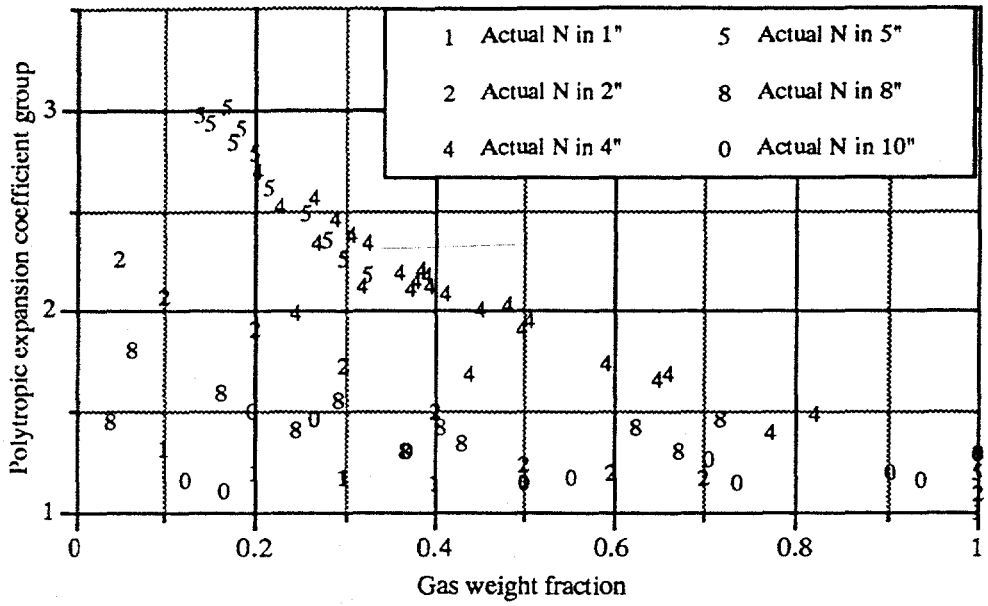


Figure 7 - Polytropic expansion coefficient group,N, as a function of the gas weight fraction for nominal diameters of 1, 2, 4, 5, 8, and 10-in.

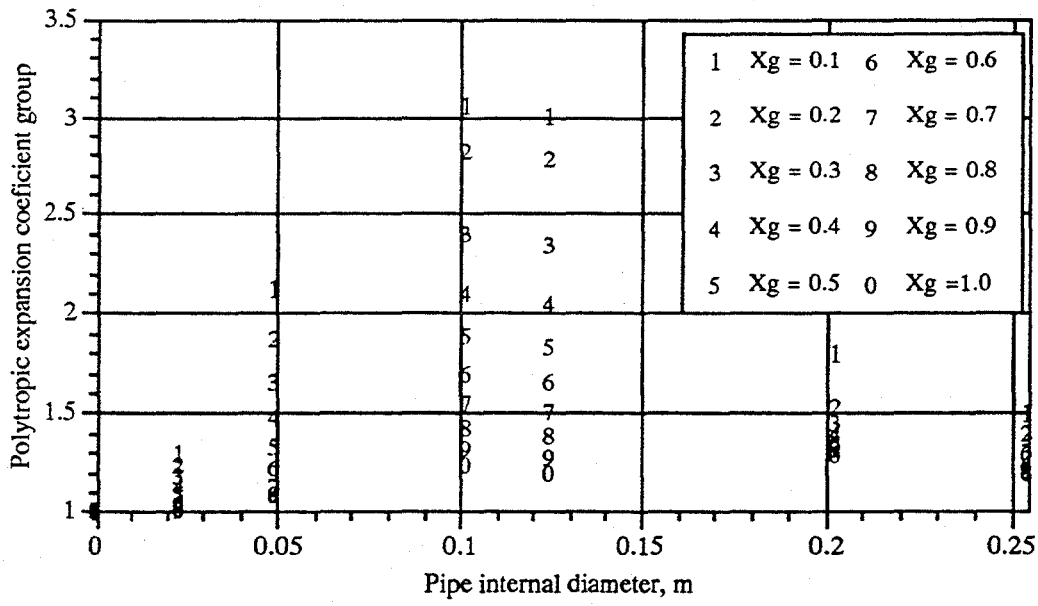


Figure 8 - Polytropic expansion coefficient group, N, as a function of the internal diameter of the pipe for gas qualities of 0.1 up to 1.0.

This graph illustrate better the features of the correlation of,N,the polytropic expansion coefficient group. A continuous line version of this scatter plot is presented in Figure 9. Figure 9 was constructed with polynomial curve fittings to the experimental data that is shown in Figure 8. The smooth curves of Figure 9 are best suited for a discussion of the main features of the correlation between the polytropic group, pipe diameter and gas weight fraction.

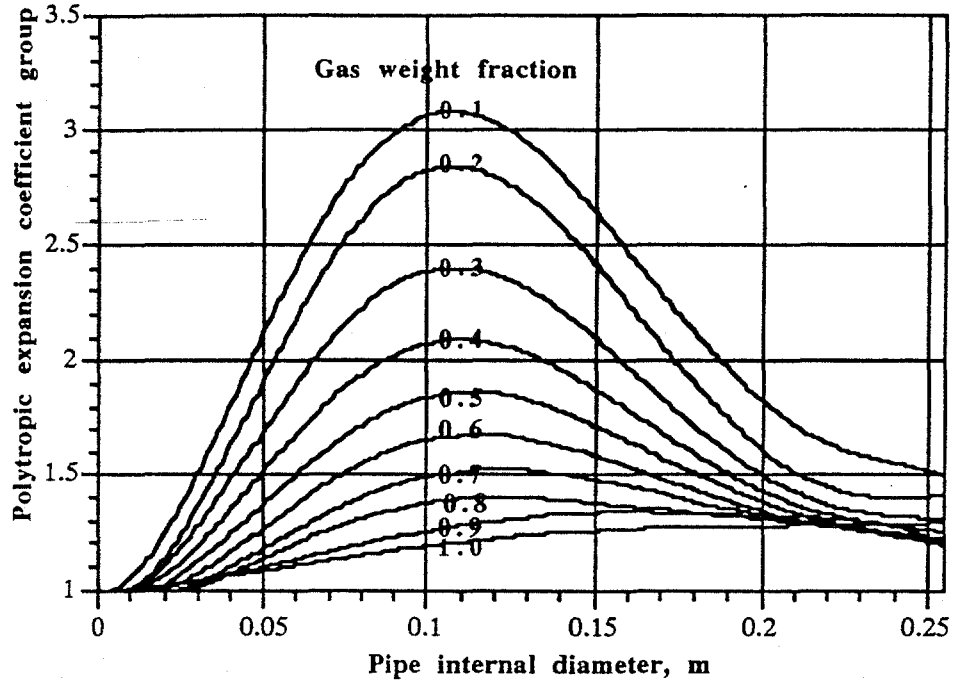


Figure 9 - Smoothed polytropic expansion coefficient group,N, as a function of the pipe internal diameter for 0.1 to 1.0 gas weight fractions.

Figure 8,and 9 clearly show that for a given gas quality, the polytropic expansion coefficient group has a maximum; the maximum value of N group decreases with increasing gas quality.,i.e,from 3.1 for a 0.1 gas quality to 1.29 for a gas quality of 1.0. Also the maximum value of the N group is a function of the pipe diameter; although a weak function for gas mass fractions lower than 0.6. In fact for gas qualities lower than 0.6, the maximum value of the N group falls in a vertical line with abscise around 0.11m (4.33-in.). For gas fractions larger than 0.6, the maximum value of N group becomes a strong function of the diameter; the maximum N group value migrates to 0.125 m. diameter.for a gas quality of 0.8, and up to 0.254 m. diameter for pure gas.

Figure 9 also shows that for vanishing pipe diameters the polytropic group tends to 1; this means that the polytropic expansion coefficient converges to the specific heat ratio, k, of the gas

Note that for diverter systems smaller than 6-in. the polytropic expansion coefficient can be directly estimated from Equation 6. However for pipe diameters 6-in. and larger, the polytropic expansion coefficient must be extracted from the general correlation introduced as Figure 9 in this work. Once the polytropic expansion coefficient group, N, is obtained from this chart, the polytopic expansion coefficient, n, is obtained from the definition given as Equation 7; however,for pipe diameters much larger than 10-in., values obtained from this correlation should be taken whit precaution. The determination of the polytropic expancion coefficient, n, is further illustrated in the following example.

Example 1 - Assume a 10-in.(0.254 m) pipe where a mixture of 0.10 gas weight fraction in water is flowing at sonic velocity. The N value read from Figure 9 gives 1.5; this results in a polytropic expansion coefficient of 1.5 x 1.33 = 2.0; this value of n = 2 lies close to the value of a 1-in. internal pipe diameter of Figure 4 which differs from the value of 4.6 predicted by Equation 6, the correlation for small diameter pipes.

Conclusions

The study of multiphase flow trough diverter systems shows, in general, that the polytropic expansion coefficient group for sonic velocities:

(1) Increases with pipe diameter increases up to a critical diameter for a fixed gas quality.

(2) Decreases with gas quality increases for a fixed pipe diameter.

(3) Converges to the specific heat ratio of the gas for vanishing pipe sizes.

(4) The polytropic expansion coefficient for sonic velocity can be obtained:

(a) From the correlation presented as Figure 4, or Equation 6 for pipes up to around 5-in. internal diameter.

(b) From the general correlation obtained in this work, and given as Figure 9.

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Nomenclature

c - Compressibility, Pa^{-1}
d - Diameter.
k - Ratio of heat capacity at constant pressure to heat capacity at constant volume.
M - Molecular weight.
n - Polytropic expansion coefficient.
p - Pressure, Pa/
R - Universal gas constant.
v - Velocity, m/s.
z - Gas deviation factor.
λ - Fractional volume or holdup.
ρ - Density, kg/m^3
χ - Weight fraction or quality.

Subscripts

a - Air
e - Effective.
g - Gas.
l - Liquid.
p - At constant pressure.
s - Solid.
v - At constant volume.