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HYDRATE: REAL MENACE TO FLOW ASSURANCE

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ABSTRACT

The effect of hydrate formation on flow was evaluated. Orifice Flow equation was applied to compute the flow rates of Gas Stream A through the orifice before hydrate formation and after hydrate formation. From the computations and Figure-3.1, it is seen that hydrate formation reduces the amount of flow through the orifice. The flow rate through the orifice before hydrate formation was 2465829.4scf/hr but after hydrate of about 2.25'' thickness was formed the flow rate reduced to 668146.4scf/hr. Also, from Figure-3.1, as the thickness of the hydrate increases, the flow rate of gas through the orifice decreases.

Keywords: natural gas stream, flow rate, hydrate, water content, orifice, inhibition.

1. INTRODUCTION

Flow assurance can be defined as an operation that provides a reliable and controlled flow of fluids from the reservoir to the sales point. Flow assurance operation deals with formation, depositions and blockages of gas hydrates, paraffin, asphaltenes, and scales that can reduce flow efficiency of oil and gas pipelines. Due to significant technical difficulties and challenges, providing safe and efficient flow assurance needs interdisciplinary focus on the issue and joined efforts of scientists, engineers and operation engineers (Guo *et al.*, 2005).

The formation of hydrates in a pipeline is common in seasonally cold or sub-sea environments with low temperatures and high pressures. In particular, hydrate blockages become a real menace to flow assurance in inadequately protected flowlines (Hunt, 1996).

Gas hydrates can form at the gas liquid interfaces along the entire length of the static pipeline. This can create small volumes of hydrate over time, but usually do not block the pipeline. However, when flow resumes, plugs can form at any point where the flow regime changes. Small-scale hydrate formation in the interface sometimes cannot be avoided in the pipeline. Moreover, under certain conditions, small-scale agglomerates are also observed in the bulk phase. Hydrate formation does not become a threat to pipe flow unless the agglomerates and hydrates formed at the interface start forming bridges. In such cases blockage occurs where the small accumulations of hydrates adhere to the walls and begin to bridge and reduce flow. This bridging can eventually shut down the entire pipeline or field until the hydrates have been removed (Austvik, 2000).

Hydrates may exist far above the freezing point of water, and hence they can cause plugging of pipelines and nozzles. Also, they may cause many difficulties in deep water drilling platform because they could block mud line, choke, and blow out preventer (BOP). For over 160 years hydrates remained a mere scientific curiosity. Their importance to the oil and gas industry was realized in the early 1930's when Hammerschmidt discovered that the solid compounds, which frequently plugged the gas transmission lines during cold weather, were not ice but hydrates (Hammerschmidt, 1934).

Hydrate formation poses challenge to natural gas pipeline, some of which are:

- **Flow restriction:** Hydrate blockages are major problem in offshore and arctic operations. They can formed in subsea transfer lines, high residence time pipelines, gas expansion cross valves due to sub-cooling effect, etc. Hydrate formation is also common in hydrocarbon transmission lines such as ethane, propane and ethylene that are operating under low temperature environment.

Figure-1 is a diagram showing a large gas hydrate plug formed in an oil and gas pipeline.

Figure-1. A large gas hydrate plug formed in a subsea hydrocarbon pipeline.
Source: Heriot-Watt University Institute of Petroleum Engineering, (2013).

2. METHODOLOGY

The flow rate of gas through the orifice is computed with equation 1 shown below:

$$Q = C^i(h_w P_f)^{0.5} \quad (1)$$

Where C^i is the Orifice flow constant expressed in equation 2 below:

$$C^i = F_b*F_r*Y*F_{pb}*F_{tb}*F_{tf}*F_g*F_{pv}*F_m*F_l*F_a \quad (2)$$

F_b = Base Orifice Factor read from the Orifice Meter Table shown in Appendix B1
F_r = Reynold's Number Factor given by equation 3 as:

$$F_r = 1+b/(h_w P_f)^{0.5} \quad (3)$$

b is read from Appendix B2
Y = Expansion Factor read from the Orifice Meter Table shown in Appendix B3 at d/D and h_w/P_f
F_{pb} = Pressure Base Factor given by equation 4 as:

$$F_{pb} = 14.73/P_b \quad (4)$$

F_{tb} = Temperature Base Factor given by equation 5 as:

$$F_{tb} = (T_b + 460)/520 \quad (5)$$

F_{tf} = Flowing Temperature Factor given by equation 6 as:

$$F_{tf} = [520/(T + 460)]^{0.5} \quad (6)$$

F_g = Specific Gravity Factor given by equation 7 as:

$$F_g = (1/SG)^{0.5} \quad (7)$$

F_{pv} = Super compressibility Factor given by equation 8 as:

$$F_{pv} = (1/z)^{0.5} \quad (8)$$

F_m = Manometer Factor given by equation 9 as:

$$F_m = [(62.3663-(P_{atm}+(h_w/27.707))/192.4)/62.3663]^{0.5} \quad (9)$$

F_l = Gauge Location Factor given by equation 10 as:

$$F_l = (g/32.17405)^{0.5} \quad (10)$$

F_a = Orifice thermal expansion factor given by equation 11 as:

$$F_a = 1 + 0.000018(T - T_m) \quad (11)$$

3. RESULTS

In order to evaluate the effect of hydrate formation on the flow of gas through flow areas, Natural Gas Stream A was taken into consideration and the work station report was obtained. The report states that hydrate is known to have formed in the orifice and the thickness of the hydrate is obtained as 2.25''. The effect of the hydrate formation on the flow of gas through the orifice is evaluated thus. The data for the evaluation is given in Table-1 below.

Table-1. Data for natural gas stream A.

Gas temperature, T, ^{0}F	35
Gas Pressure, P, psig	1200
Gas Specific Gravity, SG	0.70
Water Content of the Gas, C_w, lb/MMscf	39.3
Differential Pressure at 60^{0}F, h_w, in	65
Absolute Static Pressure, P_f, psia	2000
Orifice Size, d, in	4.75
Pipe Size, D, in	11.376
Absolute Base Pressure, P_b, psia	14.65
Absolute Base Temperature, T_b, ^{0}F	60
Gas Compressibility Factor, z	0.7
Atmospheric Pressure, P_{atm}, psia	14.4
Gravitational Acceleration, g, ft/s^2	32.1418
Temperature During Orifice Boring, T_m, ^{0}F	25

3.1 Flow through the Orifice without hydrate formation

F_b = Base Orifice Factor read from the Orifice Meter Table shown in Appendix B1 at pipe size of 11.376 as 5191.5
b is read from Appendix B2 at d = 4.75 and D = 11.376 as 0.0178
From equation 3, $F_r = 1+0.0178/(65*2000)^{0.5} = 1.000049368$
Y = Expansion Factor read from the Orifice Meter Table shown in Appendix B3 at d/D of 4.75/11.376 which is 0.418 and h_w/P_f of 0.03 as 1.003824
From equation 4, $F_{pb} = 14.73/P_b = 14.73/14.65 = 1.00546$
From equation 5, $F_{tb} = (60 + 460)/520 = 1$
From equation 6, $F_{tf} = [520/(35 + 460)]^{0.5} = 1.02494$
From equation 7, $F_g = (1/0.7)^{0.5} = 1.195$
From equation 8, $F_{pv} = (1/0.7)^{0.5} = 1.195$
From equation 9, $F_m = [(62.3663 - (14.4 + (65/27.707))/192.4)/62.3663]^{0.5} = 0.9993$
From equation 10, $F_l = (32.1418/32.17405)^{0.5} = 0.9995$
From equation 11, $F_a = 1 + 0.000018(35 - 25) = 1.00018$
From equation 2, C^i = 5191.5 * 1.000049368 * 1.003824 * 1.00546 * 1 * 1.02494 * 1.195 * 1.195 * 0.9993 * 0.9995 * 1.00018 = 7661.75
From equation 1, $Q = 7661.75 * (65 * 2000)^{0.5} = 2762482$ scf/hr

2762482scf/hr is the flow rate through the orifice without hydrate formation.

3.2 Flow through the Orifice with hydrate formation

The flow rate through the orifice after hydrate formation is computed as follows:

The New Orifice Size, d_2 = Orifice Size - Hydrate Thickness 3.1

$d_2 = 4.75 – 2.25 = 2.5$

The New Base Orifice Factor F_{b2} is read from the Orifice Meter Table shown in Appendix B1 at pipe size of 11.376 as 1295.9

For the New Reynold's Number Factor:

The New b is read from Appendix B2 at d = 2.5 and D = 11.376 as 0.0342

The New F_r, $F_{r2} = 1+0.0342/(65*2000)^{0.5} = 1.000094854$

The New Expansion Factor, Y_2 read from the Orifice Meter Table shown in Appendix B3 at d/D of 2.5/11.376 which is 0.22 and h_w/P_f of 0.03 as 0.99967

The New Flow Constant is computed as follows:
C^i = 1295.9 * 1.000094854 * 0.99967 * 1.00546 * 1 * 1.02494 * 1.195 * 1.195 * 0.9993 * 0.9995 * 1.00018 = 1904.7

The flow rate after hydrate formation is then evaluated using equation 1 as:

$Q = 1904.7 * (65 * 2000)^{0.5} = 686747.2$ scf/hr

Using equation 1, the Orifice Flow Rate at various Hydrate Thicknesses is computed and presented in Table-2 and used to generate plot of Orifice Flow Rate at various Hydrate Thicknesses as shown in Figure-1.

Table-2. Orifice flow rate at various hydrate thicknesses.

Hydrate thickness, in	Orifice flow rate, scf/hr
0	2762482.0
0.5	1959776.4
1	1517364.2
1.5	1134777.5
2	809684.8
2.5	540390.4
3	325972.3
3.5	165826.4

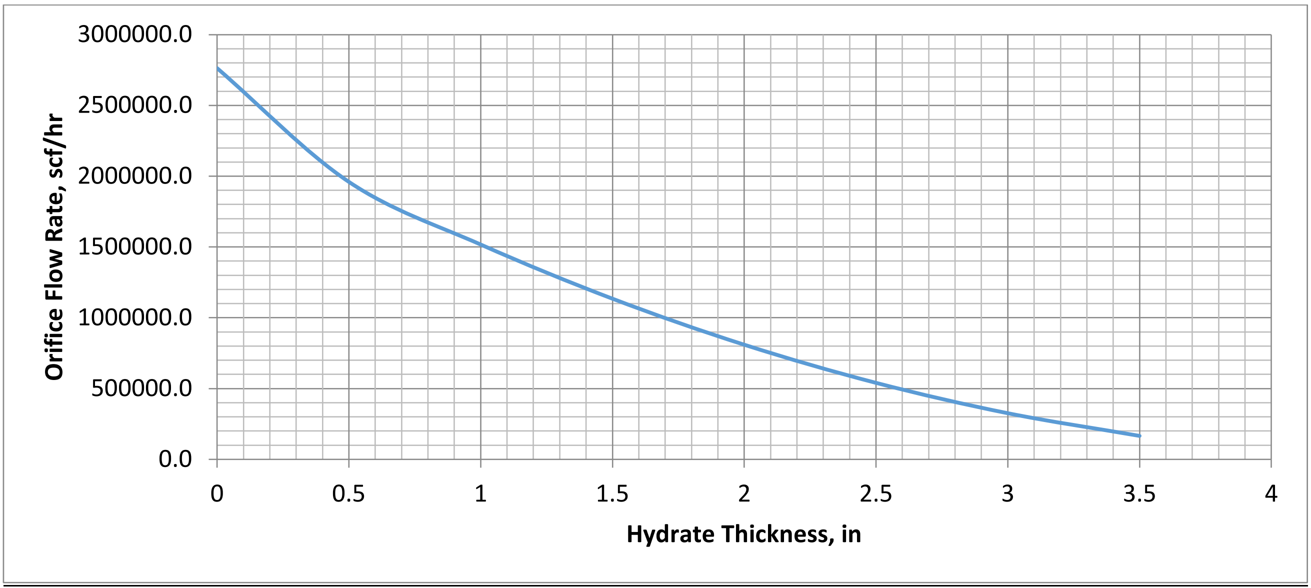

Figure-2. Orifice flow rate at various hydrate thicknesses.

4. CONCLUSIONS

From the evaluations conducted using the equations, computer models and charts, the following conclusion may be drawn:

According to Figure-2, hydrate formation reduces the amount of gas flow through the orifice. The flow rate through the orifice conducting natural gas stream A before hydrate formation was 2465829.4scf/hr but after hydrate of about 2.25'' thickness was formed the flow rate reduced to 668146.4scf/hr.

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APPENDIX A: NOMENCLATURE

C^i	= Orifice Flow Constant
D	= Pipe diameter
d	= Orifice diameter
Deg F	= Degree Fahrenheit
ft/s^2	= Foot per square second
F_b	= Base Orifice Factor read
F_r	= Reynold's Number Factor
F_{pb}	= Pressure Base Factor
F_{tb}	= Temperature Base Factor
F_{tf}	= Flowing Temperature Factor
F_g	= Specific Gravity Factor
F_{pv}	= Super compressibility Factor
F_m	= Manometer Factor
F_l	= Gauge Location Factor
F_a	= Orifice Thermal Expansion Factor
g	= Gravitational acceleration
psia	= Pound per square inch (atmosphere)
psig	= Pound per square inch (gauge)
q	= Gas flow rate
scf/hr	= Standard cubic foot per hour
SG	= Specific gravity
Y	= Expansion Factor
Z	= Compressibility factor
^0C	= Degree celsius
^0F	= Degree Fahrenheit

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APPENDIX B: ORIFICE METER TABLES

324 *Appendix C Orifice Meter Tables for Natural Gas*

Orifice Diameter (In)	10			12			18		
	9.564	10.020	10.136	11.376	11.938	12.090	14.688	15.000	15.250
1.000	202.16								
1.125	256.22	256.01	255.96						
1.250	316.90	316.56	316.49	315.84	315.57	315.51			
1.375	384.29	383.79	383.68	382.66	382.30	382.22			
1.500	458.52	457.79	457.63	456.16	455.64	455.52	453.92	453.78	
1.625	539.72	538.69	538.45	536.38	535.66	535.48	533.27	533.07	532.93
1.750	628.03	626.61	626.29	623.44	622.45	622.20	619.18	618.92	618.73
1.875	723.61	721.70	721.27	717.43	716.10	715.78	711.73	711.39	711.13
2.000	826.63	824.12	823.54	818.48	816.73	816.30	810.99	810.53	810.19
2.125	937.28	934.02	933.27	926.72	924.44	923.88	917.01	916.43	915.99
2.250	1,055.7	1,051.6	1,050.6	1,042.3	1,039.4	1,038.7	1,029.9	1,092.6	1,028.6
2.375	1,182.2	1,177.0	1,175.8	1,165.3	1,161.6	1,160.7	1,149.7	1,148.8	1,148.1
2.500	1,316.9	1,310.5	1,309.0	1,295.9	1,291.4	1,290.2	1,276.5	1,275.4	1,274.5
2.625	1,460.0	1,452.1	1,450.3	1,434.3	1,428.7	1,427.4	1,410.5	1,409.1	1,408.0
2.750	1,611.8	1,602.3	1,600.1	1,580.7	1,573.9	1,572.2	1,551.7	1,549.9	1,548.6
2.875	1,772.5	1,761.0	1,758.4	1,735.1	1,726.9	1,724.9	1,700.1	1,698.1	1,696.5
3.000	1,942.5	1,928.8	1,925.6	1,897.8	1,888.1	1,885.7	1,856.1	1,853.6	1,851.7
3.125	2,122.1	2,1057	2,102.0	2,069.0	2,057.5	2,054.7	2,019.5	2,016.6	2,014.3
3.250	2,311.6	2,292.2	2,287.8	2,248.9	2,235.4	2,232.1	2,190.7	2,187.2	2,184.5
3.375	2,511.5	2,488.6	2,483.4	2,437.7	2,421.8	2,418.0	2,369.6	2,365.5	2,362.4
3.500	2,722.3	2,695.3	2,689.1	2,635.6	2,617.2	2,612.6	2,556.5	2,551.7	2,548.1
3.625	2,944.3	2,912.7	2,905.5	2,843.0	2,821.6	2,816.3	2,751.4	2,745.9	2,741.7
3.750	3,178.1	3,141.2	3,132.7	3,060.2	3,035.3	3,029.3	2,954.5	2,948.1	2,943.3
3.875	3,424.3	3,381.3	3,371.5	3,287.4	3,258.7	3,251.7	3,165.9	3,158.6	3,153.1
4.000	3,683.5	3,633.5	3,622.1	3,524.9	3,492.0	3,483.9	3,385.8	3,377.5	3,371.2
4.250	4,243.8	4,176.8	4,161.6	4,032.8	3,989.5	3,979.0	3,851.6	3,840.9	3,832.8
4.500	4,865.1	4,776.2	4,756.1	4,587.1	4,530.8	4,517.2	4,353.4	4,339.8	4,329.6
4.750	5,554.9	5,437.9	5,411.5	5,191.5	5,119.0	5,119.0	4,892.9	4,875.8	4,862.9
5.000	6,322.2	6,169.2	6,134.9	5,850.6	5,757.8	5,757.8	5,471.9	5,450.5	5,434.3
5.250	7,177.7	6,978.9	6,934.4	6,569.4	6,451.5	6,451.5	6,092.5	6,065.9	6,045.9
5.500	8,134.1	7,877.2	7,820.0	7,354.1	7,205.1	7,205.1	6,757.0	6,724.1	6,699.4
5.750	9,207.0	8,876.3	8,803.1	8,211.4	8,024.2	8,024.2	7,468.0	7,427.6	7,397.4
6.000	10,415	9,991.2	9,897.8	9,149.5	8,915.4	8,915.4	8,228.5	8,179.2	8,142.3
6.250	11,783	11,240	11,121	10,178	9,886.1	9,886.1	9,041.6	8,981.7	8,937.0
6.500	13,340	12,644	12,492	11,307	10,945	10,945	9,911.2	9,838.7	9,764.7

Appendix-B1. Orifice Meter Table for F_b (Without Hydrate Formation)
Source: Guo and Ghalambor, (2005)

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Orifice Diameter (in)	10			12			16		
	9.564	10.02	10.136	11.376	11.938	12.09	14.688	15	15.25
1	0.0728								
1.125	0.0674	0.069	0.0694						
1.25	0.0624	0.0641	0.0646	0.0687	0.0704	0.0708			
1.375	0.0576	0.0594	0.0599	0.0643	0.0661	0.0666			
1.5	0.0532	0.055	0.0555	0.0601	0.062	0.0625	0.0697	0.0705	
1.625	0.049	0.0509	0.0514	0.0561	0.058	0.0585	0.0662	0.067	0.0676
1.75	0.0452	0.0471	0.0476	0.0523	0.0543	0.0548	0.0628	0.0636	0.0642
1.875	0.0417	0.0436	0.044	0.0488	0.0508	0.0513	0.0594	0.0603	0.061
2	0.0385	0.0403	0.0407	0.0454	0.0475	0.048	0.0563	0.0572	0.0578
2.125	0.0355	0.0372	0.0377	0.0423	0.0443	0.0449	0.0532	0.0541	0.0548
2.25	0.0329	0.0345	0.0349	0.0394	0.0414	0.0419	0.0503	0.0512	0.0519
2.375	0.0305	0.032	0.0324	0.0367	0.0387	0.0392	0.0475	0.0484	0.0492
2.5	0.0283	0.0298	0.0301	0.0342	0.0361	0.0366	0.0449	0.0458	0.0466
2.625	0.0265	0.0277	0.0281	0.0319	0.0337	0.0342	0.0424	0.0433	0.044
2.75	0.0248	0.026	0.0262	0.0298	0.0316	0.032	0.04	0.0409	0.0417
2.875	0.0234	0.0244	0.0246	0.0279	0.0295	0.03	0.0378	0.0387	0.0394
3	0.0222	0.023	0.0232	0.0262	0.0277	0.0281	0.0356	0.0365	0.0372
3.125	0.0212	0.0218	0.022	0.0244	0.026	0.0264	0.0336	0.0345	0.0352
3.25	0.0204	0.0209	0.0221	0.0232	0.0245	0.0249	0.0317	0.0326	0.0332
3.375	0.0199	0.0201	0.0202	0.022	0.0232	0.0235	0.03	0.0308	0.0314
3.5	0.0195	0.0195	0.0196	0.021	0.022	0.0222	0.0263	0.0291	0.0297
3.625	0.0193	0.0191	0.0191	0.02	0.0209	0.0212	0.0368	0.0275	0.0281
3.75	0.0192	0.0188	0.0188	0.0193	0.02	0.0202	0.0254	0.0261	0.0267
3.875	0.0193	0.0187	0.0186	0.0187	0.0192	0.0194	0.024	0.0247	0.0253
4	0.0195	0.0187	0.0186	0.0182	0.0185	0.0187	0.0228	0.0235	0.024
4.25	0.0203	0.0192	0.0189	0.0176	0.0196	0.0177	0.0207	0.0213	0.0217
4.5	0.0215	0.02	0.0197	0.0175	0.0172	0.0171	0.019	0.0194	0.0198
4.75	0.023	0.0212	0.0208	0.0178	0.0171	0.017	0.0176	0.018	0.0182
5	0.0248	0.0228	0.0223	0.0185	0.0174	0.0173	0.0166	0.0168	0.017
5.25	0.0267	0.0244	0.0239	0.0194	0.0181	0.0178	0.016	0.0161	0.0162
5.5	0.0287	0.0263	0.0257	0.0207	0.019	0.0186	0.0156	0.0156	0.0156
5.75	0.0307	0.0282	0.0276	0.0221	0.0202	0.0197	0.0155	0.0154	0.0153
6	0.0326	0.0302	0.0295	0.0231	0.0215	0.021	0.0157	0.0154	0.0153
6.25	0.0343	0.032	0.0316	0.0253	0.023	0.0224	0.0161	0.0157	0.0154
6.5	0.0358	0.0336	0.0331	0.027	0.0246	0.0239	0.0167	0.0162	0.0159

Appendix-B2. Orifice Meter Table for b (Without Hydrate Formation)
Source: Guo and Ghalambor, (2005)

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Table C-9 Y_2 Expansion Factors—Pipe Taps (Static Pressure Taken from Downstream Taps)

$$\beta = \frac{d}{D}$$

$\frac{h_w}{P_{f2}}$	0.10	0.20	0.30	0.40	0.45	0.50	0.52	0.54	0.56	0.58	0.60	0.61	0.62	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.70
0.1	1.0008	1.0008	1.0006	1.0003	1.0002	1.0000	0.9999	0.9998	0.9997	0.9996	0.9995	0.9994	0.9994	0.9993	0.9992	0.9991	0.999	0.9989	0.9988	0.9987	0.9986
0.2	1.0017	1.0015	1.0012	1.0007	1.0004	1.0000	0.9999	0.9997	0.9995	0.9993	0.999	0.9989	0.9988	0.9986	0.9985	0.9983	0.9981	0.9979	0.9977	0.9974	0.9972
0.3	1.0025	1.0023	1.0018	1.001	1.0006	1.0000	0.9998	0.9995	0.9992	0.9989	0.9986	0.9984	0.9982	0.9979	0.9977	0.9974	0.9972	0.9969	0.9965	0.9962	0.9958
0.4	1.0034	1.003	1.0024	1.0014	1.0008	1.0001	0.9997	0.9994	0.999	0.9986	0.9981	0.9978	0.9976	0.9972	0.9969	0.9966	0.9962	0.9958	0.9954	0.9949	0.9944
0.5	1.0042	1.0038	1.003	1.0018	1.001	1.0001	0.9997	0.9992	0.9988	0.9982	0.9976	0.9973	0.997	0.9966	0.9962	0.9958	0.9953	0.9948	0.9942	0.9936	0.993
0.6	1.0051	1.0045	1.0036	1.0021	1.0012	1.0001	0.9996	0.9991	0.9985	0.9979	0.9972	0.9968	0.9964	0.9959	0.9954	0.9949	0.9944	0.9938	0.9931	0.9924	0.9916
0.7	1.0059	1.0053	1.0041	1.0025	1.0014	1.0002	0.9996	0.999	0.9983	0.9975	0.9967	0.9962	0.9958	0.9953	0.9947	0.9941	0.9935	0.9928	0.992	0.9912	0.9902
0.8	1.0068	1.006	1.0047	1.0028	1.0016	1.0002	0.9995	0.9988	0.998	0.9972	0.9962	0.9957	0.9952	0.9946	0.994	0.9933	0.9926	0.9918	0.9909	0.9899	0.9889
0.9	1.0076	1.0068	1.0053	1.0032	1.0018	1.0002	0.9995	0.9987	0.9978	0.9969	0.9958	0.9952	0.9946	0.994	0.9932	0.9925	0.9917	0.9908	0.9898	0.9887	0.9875
1	1.0085	1.0075	1.0059	1.0036	1.0021	1.0003	0.9994	0.9986	0.9976	0.9965	0.9954	0.9947	0.994	0.9933	0.9925	0.9917	0.9908	0.9898	0.9887	0.9875	0.9862
1.1	1.0093	1.0083	1.0065	1.0039	1.0023	1.0003	0.9994	0.9984	0.9974	0.9962	0.9949	0.9942	0.9935	0.9927	0.9918	0.9909	0.9899	0.9888	0.9876	0.9863	0.9848
1.2	1.0102	1.0091	1.0071	1.0043	1.0025	1.0004	0.9994	0.9983	0.9972	0.9959	0.9945	0.9937	0.9929	0.992	0.9911	0.9901	0.989	0.9878	0.9865	0.9851	0.9835
1.3	1.011	1.0098	1.0077	1.0047	1.0027	1.0004	0.9994	0.9982	0.997	0.9956	0.9941	0.9932	0.9924	0.9914	0.9904	0.9893	0.9881	0.9868	0.9854	0.9839	0.9822
1.4	1.0119	1.0106	1.0083	1.0051	1.003	1.0004	0.9993	0.9981	0.9968	0.9953	0.9936	0.9928	0.9918	0.9908	0.9897	0.9885	0.9872	0.9859	0.9844	0.9827	0.9809
1.5	1.0127	1.0113	1.0089	1.0054	1.0032	1.0005	0.9993	0.998	0.9966	0.995	0.9932	0.9923	0.9912	0.9902	0.989	0.9877	0.9864	0.9849	0.9833	0.9815	0.9796
1.6	1.0136	1.0121	1.0096	1.0058	1.0034	1.0006	0.9993	0.9979	0.9964	0.9947	0.9928	0.9918	0.9907	0.9896	0.9883	0.987	0.9855	0.984	0.9822	0.9804	0.9783
1.7	1.0144	1.0128	1.0102	1.0062	1.0036	1.0006	0.9992	0.9978	0.962	0.9944	0.9924	0.9913	0.9902	0.9889	0.9876	0.9862	0.9847	0.983	0.9812	0.9792	0.977
1.8	1.0153	1.0136	1.0108	1.0066	1.0039	1.0007	0.9992	0.9977	0.996	0.9941	0.992	0.9908	0.9896	0.9883	0.987	0.9854	0.9838	0.9821	0.9801	0.978	0.9757
1.9	1.0161	1.0144	1.0114	1.007	1.0041	1.0008	0.9992	0.9976	0.9958	0.9938	0.9916	0.9904	0.9891	0.9877	0.9863	0.9847	0.983	0.9811	0.9791	0.9769	0.9744

Appendix-B3. Orifice Meter Table for Y (Without Hydrate Formation)
Source: Guo and Ghalambor, (2005)

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Orifice Diameter (in)	10			12			18		
	9.564	10.020	10.136	11.376	11.938	12.090	14.688	15.000	15.250
1.000	202.16								
1.125	256.22	256.01	255.96						
1.250	316.90	316.56	316.49	315.84	315.57	315.51			
1.375	384.29	383.79	383.68	382.66	382.30	382.22			
1.500	458.52	457.79	457.63	456.16	455.64	455.52	453.92	453.78	
1.625	539.72	538.69	538.45	536.38	535.66	535.48	533.27	533.07	532.93
1.750	628.03	626.61	626.29	623.44	622.45	622.20	619.18	618.92	618.73
1.875	723.61	721.70	721.27	717.43	716.10	715.78	711.73	711.39	711.13
2.000	826.63	824.12	823.54	818.48	816.73	816.30	810.99	810.53	810.19
2.125	937.28	934.02	933.27	926.72	924.44	923.88	917.01	916.43	915.99
2.250	1,055.7	1,051.6	1,050.6	1,042.3	1,039.4	1,038.7	1,029.9	1,092.6	1,028.6
2.375	1,182.2	1,177.0	1,175.8	1,165.3	1,161.6	1,160.7	1,149.7	1,148.8	1,148.1
2.500	1,316.9	1,310.5	1,309.0	1,295.9	1,291.4	1,290.2	1,276.5	1,275.4	1,274.5
2.625	1,460.0	1,452.1	1,450.3	1,434.3	1,428.7	1,427.4	1,410.5	1,409.1	1,408.0
2.750	1,611.8	1,602.3	1,600.1	1,580.7	1,573.9	1,572.2	1,551.7	1,549.9	1,548.6
2.875	1,772.5	1,761.0	1,758.4	1,735.1	1,726.9	1,724.9	1,700.1	1,698.1	1,696.5
3.000	1,942.5	1,928.8	1,925.6	1,897.8	1,888.1	1,885.7	1,856.1	1,853.6	1,851.7
3.125	2,122.1	2,1057	2,102.0	2,069.0	2,057.5	2,054.7	2,019.5	2,016.6	2,014.3
3.250	2,311.6	2,292.2	2,287.8	2,248.9	2,235.4	2,232.1	2,190.7	2,187.2	2,184.5
3.375	2,511.5	2,488.6	2,483.4	2,437.7	2,421.8	2,418.0	2,369.6	2,365.5	2,362.4
3.500	2,722.3	2,695.3	2,689.1	2,635.6	2,617.2	2,612.6	2,556.5	2,551.7	2,548.1
3.625	2,944.3	2,912.7	2,905.5	2,843.0	2,821.6	2,816.3	2,751.4	2,745.9	2,741.7
3.750	3,178.1	3,141.2	3,132.7	3,060.2	3,035.3	3,029.3	2,954.5	2,948.1	2,943.3
3.875	3,424.3	3,381.3	3,371.5	3,287.4	3,258.7	3,251.7	3,165.9	3,158.6	3,153.1
4.000	3,683.5	3,633.5	3,622.1	3,524.9	3,492.0	3,483.9	3,385.8	3,377.5	3,371.2
4.250	4,243.8	4,176.8	4,161.6	4,032.8	3,989.5	3,979.0	3,851.6	3,840.9	3,832.8
4.500	4,865.1	4,776.2	4,756.1	4,587.1	4,530.8	4,517.2	4,353.4	4,339.8	4,329.6
4.750	5,554.9	5,437.9	5,411.5	5,191.5	5,119.0	5,119.0	4,892.9	4,875.8	4,862.9
5.000	6,322.2	6,169.2	6,134.9	5,850.6	5,757.8	5,757.8	5,471.9	5,450.5	5,434.3
5.250	7,177.7	6,978.9	6,934.4	6,569.4	6,451.5	6,451.5	6,092.5	6,065.9	6,045.9
5.500	8,134.1	7,877.2	7,820.0	7,354.1	7,205.1	7,205.1	6,757.0	6,724.1	6,699.4
5.750	9,207.0	8,876.3	8,803.1	8,211.4	8,024.2	8,024.2	7,468.0	7,427.6	7,397.4
6.000	10,415	9,991.2	9,897.8	9,149.5	8,915.4	8,915.4	8,228.5	8,179.2	8,142.3
6.250	11,783	11,240	11,121	10,178	9,886.1	9,886.1	9,041.6	8,981.7	8,937.0
6.500	13,340	12,644	12,492	11,307	10,945	10,945	9,911.2	9,838.7	9,764.7

Appendix-B4. Orifice Meter Table for F_b (With Hydrate Formation)
Source: Guo and Ghalambor, (2005)

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330 *Appendix C Orifice Meter Tables for Natural Gas*

Orifice Diameter (in)	10			12			16		
	9.564	10.02	10.136	11.376	11.938	12.09	14.688	15	15.25
1	0.0728								
1.125	0.0674	0.069	0.0694						
1.25	0.0624	0.0641	0.0646	0.0687	0.0704	0.0708			
1.375	0.0576	0.0594	0.0599	0.0643	0.0661	0.0666			
1.5	0.0532	0.055	0.0555	0.0601	0.062	0.0625	0.0697	0.0705	
1.625	0.049	0.0509	0.0514	0.0561	0.058	0.0585	0.0662	0.067	0.0676
1.75	0.0452	0.0471	0.0476	0.0523	0.0543	0.0548	0.0628	0.0636	0.0642
1.875	0.0417	0.0436	0.044	0.0488	0.0508	0.0513	0.0594	0.0603	0.061
2	0.0385	0.0403	0.0407	0.0454	0.0475	0.048	0.0563	0.0572	0.0578
2.125	0.0355	0.0372	0.0377	0.0423	0.0443	0.0449	0.0532	0.0541	0.0548
2.25	0.0329	0.0345	0.0349	0.0394	0.0414	0.0419	0.0503	0.0512	0.0519
2.375	0.0305	0.032	0.0324	0.0367	0.0387	0.0392	0.0475	0.0484	0.0492
2.5	0.0283	0.0298	0.0301	0.0342	0.0361	0.0366	0.0449	0.0458	0.0466
2.625	0.0265	0.0277	0.0281	0.0319	0.0337	0.0342	0.0424	0.0433	0.044
2.75	0.0248	0.026	0.0262	0.0298	0.0316	0.032	0.04	0.0409	0.0417
2.875	0.0234	0.0244	0.0246	0.0279	0.0295	0.03	0.0378	0.0387	0.0394
3	0.0222	0.023	0.0232	0.0262	0.0277	0.0281	0.0356	0.0365	0.0372
3.125	0.0212	0.0218	0.022	0.0244	0.026	0.0264	0.0336	0.0345	0.0352
3.25	0.0204	0.0209	0.0221	0.0232	0.0245	0.0249	0.0317	0.0326	0.0332
3.375	0.0199	0.0201	0.0202	0.022	0.0232	0.0235	0.03	0.0308	0.0314
3.5	0.0195	0.0195	0.0196	0.021	0.022	0.0222	0.0263	0.0291	0.0297
3.625	0.0193	0.0191	0.0191	0.02	0.0209	0.0212	0.0368	0.0275	0.0281
3.75	0.0192	0.0188	0.0188	0.0193	0.02	0.0202	0.0254	0.0261	0.0267
3.875	0.0193	0.0187	0.0186	0.0187	0.0192	0.0194	0.024	0.0247	0.0253
4	0.0195	0.0187	0.0186	0.0182	0.0185	0.0187	0.0228	0.0235	0.024
4.25	0.0203	0.0192	0.0189	0.0176	0.0196	0.0177	0.0207	0.0213	0.0217
4.5	0.0215	0.02	0.0197	0.0175	0.0172	0.0171	0.019	0.0194	0.0198
4.75	0.023	0.0212	0.0208	0.0178	0.0171	0.017	0.0176	0.018	0.0182
5	0.0248	0.0228	0.0223	0.0185	0.0174	0.0173	0.0166	0.0168	0.017
5.25	0.0267	0.0244	0.0239	0.0194	0.0181	0.0178	0.016	0.0161	0.0162
5.5	0.0287	0.0263	0.0257	0.0207	0.019	0.0186	0.0156	0.0156	0.0156
5.75	0.0307	0.0282	0.0276	0.0221	0.0202	0.0197	0.0155	0.0154	0.0153
6	0.0326	0.0302	0.0295	0.0231	0.0215	0.021	0.0157	0.0154	0.0153
6.25	0.0343	0.032	0.0316	0.0253	0.023	0.0224	0.0161	0.0157	0.0154
6.5	0.0358	0.0336	0.0331	0.027	0.0246	0.0239	0.0167	0.0162	0.0159

Appendix-B5. Orifice Meter Table for b (With Hydrate Formation)
Source: Guo and Ghalambor, (2005)

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Table C-8 Y_1 Expansion Factors—Pipe Taps (Static Pressure Taken from Upstream Taps)

$$\beta = \frac{d}{D}$$

$\frac{h_w}{P_{f1}}$	0.10	0.20	0.30	0.40	0.45	0.50	0.52	0.54	0.56	0.58	0.60	0.61	0.62	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.70
0.1	0.999	0.9989	0.9988	0.9985	0.9984	0.9982	0.9981	0.998	0.9979	0.9978	0.9977	0.9976	0.9976	0.9975	0.9974	0.9973	0.9972	0.9971	0.997	0.9969	0.9968
0.2	0.9981	0.9979	0.9976	0.9971	0.9968	0.9964	0.9962	0.9961	0.9959	0.9957	0.9954	0.9953	0.9951	0.995	0.9948	0.9947	0.9945	0.9943	0.9941	0.9938	0.9935
0.3	0.9971	0.9968	0.9964	0.9956	0.9952	0.9946	0.9944	0.9941	0.9938	0.9935	0.9931	0.9929	0.9927	0.9925	0.9923	0.992	0.9917	0.9914	0.9911	0.9907	0.9903
0.4	0.9962	0.9958	0.9951	0.9942	0.9936	0.9928	0.9925	0.9921	0.9917	0.9913	0.9908	0.9906	0.9903	0.99	0.9897	0.9893	0.989	0.9686	0.9881	0.9876	0.9871
0.5	0.9952	0.9947	0.9939	0.9927	0.9919	0.991	0.9906	0.9902	0.9897	0.9891	0.9885	0.9882	0.9879	0.9875	0.9871	0.9867	0.9862	0.9857	0.9851	0.9845	0.9839
0.6	0.9943	0.9937	0.9927	0.9913	0.9903	0.9892	0.9887	0.9882	0.9876	0.987	0.9862	0.9859	0.9854	0.985	0.9845	0.984	0.9834	0.9828	0.9822	0.9814	0.9806
0.7	0.9933	0.9926	0.9915	0.9898	0.9887	0.9874	0.9869	0.9862	0.9856	0.9848	0.984	0.9835	0.983	0.9825	0.9819	0.9813	0.9807	0.98	0.9792	0.9784	0.9774
0.8	0.9923	0.9916	0.9903	0.9883	0.9871	0.9857	0.985	0.9843	0.9835	0.9826	0.9817	0.9811	0.9806	0.98	0.9794	0.9787	0.9779	0.9771	0.9762	0.9753	0.9742
0.9	0.9914	0.9905	0.9891	0.9869	0.9855	0.9839	0.9831	0.9823	0.9814	0.9805	0.9794	0.9788	0.9782	0.9775	0.9768	0.976	0.9752	0.9742	0.9733	0.9722	0.971
1	0.9904	0.9895	0.9878	0.9854	0.9839	0.9821	0.9812	0.9803	0.9794	0.9783	0.9771	0.9764	0.9757	0.975	0.9742	0.9733	0.9724	0.9714	0.9703	0.9691	0.9677
1.1	0.9895	0.9884	0.9866	0.984	0.9823	0.9803	0.9794	0.9784	0.9773	0.9761	0.9748	0.9741	0.9733	0.9725	0.9716	0.9707	0.9696	0.9685	0.9673	0.966	0.9645
1.2	0.9885	0.9874	0.9854	0.9825	0.9807	0.9785	0.9775	0.9764	0.9752	0.9739	0.9725	0.9717	0.9709	0.97	0.969	0.968	0.9669	0.9757	0.9643	0.9629	0.9613
1.3	0.9876	0.9863	0.9842	0.9811	0.9791	0.9767	0.9756	0.9744	0.9732	0.9718	0.9702	0.9694	0.9685	0.9675	0.9664	0.9653	0.9641	0.9628	0.9614	0.9598	0.9581
1.4	0.9866	0.9853	0.983	0.9796	0.9775	0.9749	0.9737	0.9725	0.9711	0.9696	0.9679	0.967	0.966	0.965	0.9639	0.9627	0.9614	0.9599	0.9584	0.9567	0.9548
1.5	0.9857	0.9842	0.9818	0.9782	0.9758	0.9731	0.9719	0.9705	0.969	0.9674	0.9656	0.9646	0.9636	0.9625	0.9613	0.96	0.9586	0.9571	0.9554	0.9536	0.9516
1.6	0.9847	0.9832	0.9805	0.9767	0.9742	0.9713	0.97	0.9685	0.967	0.9652	0.9633	0.9623	0.9612	0.96	0.9587	0.9573	0.9558	0.9542	0.9525	0.9505	0.9484
1.7	0.9837	0.9821	0.9793	0.9752	0.9726	0.9695	0.9681	0.9666	0.9649	0.9631	0.961	0.9599	0.9587	0.9575	0.9561	0.9547	0.9531	0.9514	0.9495	0.9474	0.9452
1.8	0.9828	0.9811	0.9781	0.9738	0.971	0.9677	0.9662	0.9646	0.9628	0.9609	0.9587	0.9576	0.9563	0.955	0.9535	0.952	0.9503	0.9485	0.9465	0.9443	0.9419
1.9	0.9818	0.98	0.9769	0.9723	0.9694	0.9659	0.9643	0.9626	0.9608	0.9587	0.9565	0.9552	0.9539	0.9525	0.951	0.9493	0.9476	0.9456	0.9435	0.9412	0.9387
2	0.9809	0.979	0.9757	0.9709	0.9678	0.9641	0.9625	0.9607	0.9587	0.9566	0.9542	0.9529	0.9515	0.95	0.9484	0.9467	0.9448	0.9428	0.9406	0.9381	0.9355
2.1	0.9799	0.9778	0.9745	0.9694	0.9662	0.9623	0.9606	0.9587	0.9566	0.9544	0.9519	0.9505	0.949	0.9475	0.9458	0.944	0.942	0.9399	0.9376	0.9351	0.9323

Appendix-B6. Orifice Meter Table for Y (With Hydrate Formation)
Source: Guo and Ghalambor, (2005)