TWO PIECE PLUNGER TEST RESULTS

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INTRODUCTION

Before discussing the two piece plunger some introductory discussion is presented on conventional plungers and their cycle of operation. The literature provides [1-8] background information on conventional plunger lift.

The steps in the conventional plunger cycle shown in Figure 1:

(1) Well is closed in: pressure builds to needed value in the casing which will expand into the tubing and lift the plunger and associated liquids when the well is opened. If the amount of liquid present above the plunger is small, then the casing pressure builds to needed value quicker.

(2) Plunger rises: As the plunger rises, a good seal needed between the plunger and the tubing ID to prevent gas from bypassing the plunger. A value of about 750 ft/min average velocity during the rise period is often mentioned in the industry as good practice.

(3) Plunger surfaces: The liquid above the plunger is produced from the well. It is not uncommon to detect some liquids following the plunger. The well pressure holds the plunger at the surface. Gas production commences.

(4) Gas produces to low rate: As gas velocity drops with the plunger at the surface, liquids accumulate in the tubing. This is the concept that as liquids drop below a "critical" velocity, liquids are no longer efficiently carried from the well. The longer the well is allowed to flow at a low rate, the more liquids will accumulate in the well for the next cycle. It is desirable to keep the liquid slug size to a small value to optimize production.

(5) Plunger falls: From manual or computer controlled signal, the production valve is closed. For optimum production, the plunger needs to fall fast, collect liquids, and return when pressure builds to a needed value in the casing. Many conventional plungers have mechanical devices that open sealing mechanisms or open a passage though or around the plunger so it will fall faster when the well is closed.

The conventional plunger (cycle discussed above) needs a shut-in period to build up casing pressure and during this period, production is greatly reduced.

The two piece plunger is considerably different in construction and in the way it cycles in the well. See Appendices for illustrations of the two piece plunger and the test facility in which performance data was collected.

Below the two-piece plunger cycle is presented and discussed:

1. Figure 2 begins with the tubing production automated valve open and the two piece plunger sealed with the ball on the bottom of the cylinder bringing up a slug of liquid.

2. When the surface is reached, the cylinder comes over a downward facing rod and the rod pushes the ball from the bottom of the cylinder and the ball falls (if the production is not too much). The cylinder remains on the rod while production flows up between the rod and the ID of the cylinder. The flow time-period when the cylinder is at the surface has to be long enough to allow the ball a head start, or the cylinder will catch it before it reaches bottom.

3. Typically when flow becomes lower, the well is shut in for approximately 10 seconds which is presumed long enough for the cylinder to fall off the rod and then begin to fall to the bottom to re-join with the ball which is presumed to already be at the bottom of the tubing on a bumper spring.

4. The cylinder rejoins the ball at the bottom on the bumper spring.

5. The ball seals the bottom of the cylinder and the ball and cylinder travel upward again carrying accumulated liquids to the surface similar to what a conventional plunger would do.

Since the shut-in time is minimal, this has resulted in increased production for many applications of the two piece plunger with results from one successful application[9] shown below in Figure 3. See also information by Gates[10].
However since the ball and cylinder fall against the flow some testing was done to see against what well pressures and flow rates the ball and cylinder fall. Since some applications of the two piece plunger do not respond with increased production, it could be because the components may not fall against higher production rates in the tubing.

Appendix C shows how drag coefficients of the ball and cylinder and the ball/cylinder were determined by suspending the components and determining drag coefficients. This data is then used to estimate fall and rise velocities at other conditions.

Examples of using the charts developed: 2" Titanium ball and plunger (cylinder)
Consider Figure B.2 in Appendix B concerning falling of the ball.

Data: 400 Mscf/D production and 200 psia. This is about critical flow (492 Mscf/D is critical) so liquids are accumulating in the well according to this criteria. The definition of critical rate using Turner[11] is below using surface well P_{wh} and T_{wh}:

$$q_{t,water}(MMscf/D) = \frac{0.0890 P_{wh} D_{tbg}^2}{(T_{wh}+460)z} \frac{(67-0.0031P_{wh})^{1/4}}{(0.0031P_{wh})^{1/2}}$$

Reading the figure B2, the ball is predicted to fall at about 1000 fpm so this is very acceptable. If the well has this pressure and is flowing this rate, then when the ball is pushed from then end of the cylinder at the well surface when the cylinder slides up and over the rod, then the ball will fall to the bottom of the well as intended.

Data; 1000 Mscf/D and 500 psia. Reading Figure B.2, the ball is estimated to fall at a little more than 200 fpm in natural gas. This is fairly slow. It would take 50 minutes to fall in a 10,000' well. However this current flow is above critical (critical rate =775 Mscf/D) so the rate must decline before liquids begin to accumulate below.

If the well continues to produce 1000 Mscf/D after the ball is dropped, then you must continue to flow with the cylinder at the surface for 50 minutes for the ball to reach bottom first. However from Figure B.4 for the cylinder, it would travel at about 800 fpm so you could release the cylinder 10,000'/800 fpm = 12.5 minutes earlier or at 37.5 minutes after the ball starts to fall, and then the cylinder and ball would hit about the same time at bottom. Of course if you released the cylinder later, the ball would be on bottom .

If the well does not drop in rate significantly in time, it might be more desirable to choke the well , for example, back to around 600 psia and 500 Mscf/D and then you would only have to flow the well for a minimum of 10,000'/700 fpm $\approx$ 15 minutes to insure the ball has reached the bottom before releasing the cylinder. Since the cylinder would fall at about 1200 fpm (Figure B.4) it would reach bottom in 8.33 minutes so considering this you could release the cylinder after as short a time of 15-8.33 = 6.67 minutes and the ball and cylinder would hit bottom at about the same time. However there is the complication that holding the flow at 500 Mscf/D at 600 psia is below critical flow rate (critical flow rate ~ 848 Mscf/D) so you would not want to hold it here for long because liquids would accumulate. Releasing the cylinder at a later time would be fine as well to insure the components combine at the bottom of the well. A later release time would be more determined by what cycles best fit the well for best production.

In conclusion, test data indicates that the ball especially may not fall at desired velocities against higher flow rates. Use the charts to examine different conditions than were shown by example here. If the ball is predicted to fall slowly, then the well would have to be reduced in flow or choked back with the cylinder at the surface to insure that the ball reaches bottom or near bottom before releasing the cylinder. Then the well could be shut in for a short time to release the cylinder. If this is not done for higher rates, then the ball and cylinder will not re-combine at the bottom of the well. This would defeat the cycle and for that cycle, little or no liquids would be removed from the well. This could periodically or regularly occur with little indication to the operator, unless very careful attention is focused on the well. Avoid choking the well back to below critical rates for extended periods of time beyond the time for the components to reach bottom.

If the ball and cylinder are dropped in air at low pressures, they both fall at about 2000 fpm. Using this data, fall velocities with hydrocarbon gasses at different pressures could be calculated using the techniques presented here.

SUMMARY & CONCLUSIONS

The two piece plunger has shown production improvement in many instances. In some cases no response may be due to the production flow rate being too high to let the components fall. Fall rates for the ball and cylinder for the two piece plunger are determined from full scale tubing tests. Charts are developed for the user to estimate fall velocities for various conditions which may result in the user choking the well back to a lower rate when the plunger hit's the surface to allow the ball to fall. However you must also consider that if you choke the well back below critical flow rate11, liquids will be accumulating so you would not want to choke it back for a long time, especially if it was flowing above critical beforehand. This shows that proper operation must be a balance of flow and pressure such that the components will fall and that if you need to choke the well back, you should not choke it back below critical, or if you do choke it back below critical, you do so for a short time only. Not all ramifications of considering fall times and critical rates have been considered at this time.

The time required for the cylinder to fall can be calculated to see how long it takes to reach bottom after perhaps a 10 second shut-in to drop the cylinder off the rod at surface.
Use of the drag model developed could be used to decide when a ball and cylinder of heavier material would be advisable.
Flow controls on the tubing that activate a casing motor valve, could be used to maintain an effective flow rate on the tubing, while producing excess gas up the casing on wells that have packer-less completions.
Automation could be used to create reduced-flow, ball and cylinder, drop times as a part of the plunger cycle.

The models do not predict the effects of fluids coming with the gas and accounting for these effects will require additional experimentation. However since most liquids are cleared when the plunger reaches the surface, the results may be applicable.

Additional experimental data at different pressures, suspension with liquids flowing, and fall and rise velocities at different conditions are all concerns for additional testing. Additional testing will determine if drag coefficients can be determined more accurately, if they change appreciably with flow and pressure, and how liquids affect the rise and fall of the components.

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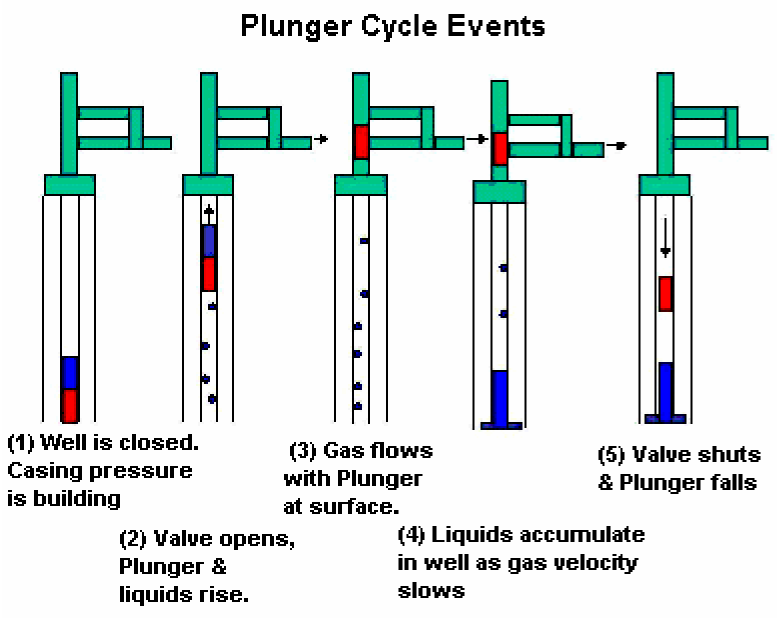


Figure 1- Conventional Plunger Cycle

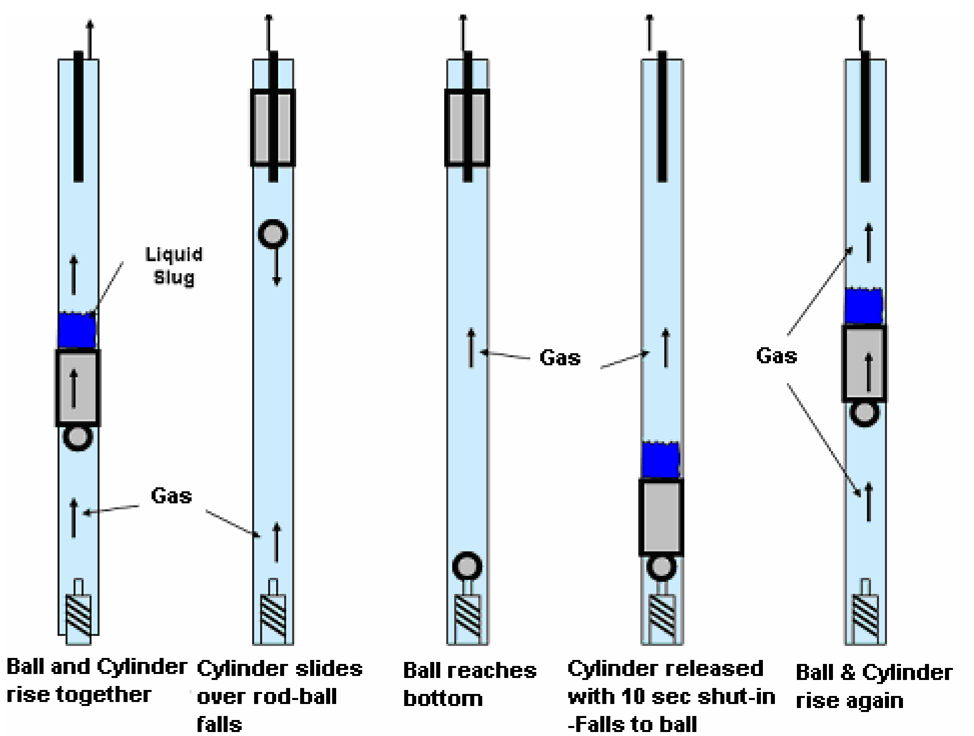


Figure 2 - Typical Two-Piece Plunger Cycle

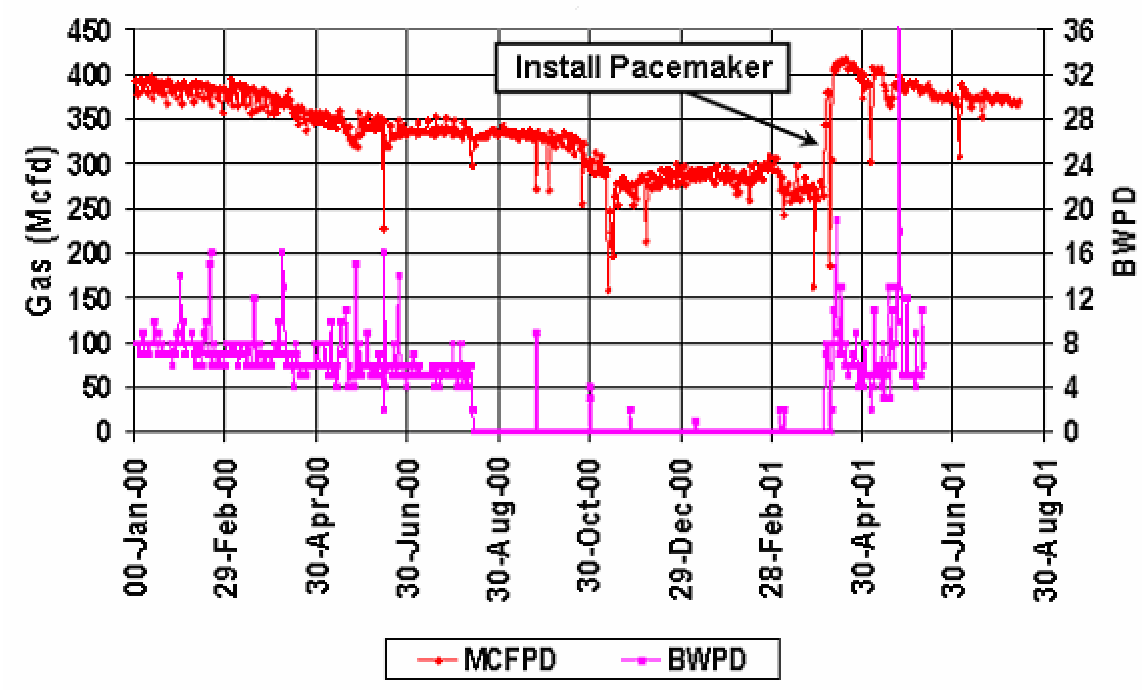


Figure 3 - Production Increase using Two-Piece Plunger vs. Conventional Plunger (From Letz[9])

Appendix A
Equipment and Facilities Illustrations

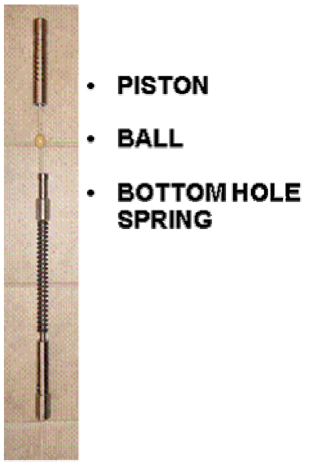


Figure A.1 - Two Piece Plunger Well Equipment: For Bottomhole and Surface

Figure A-2 - Two-Piece Plungers

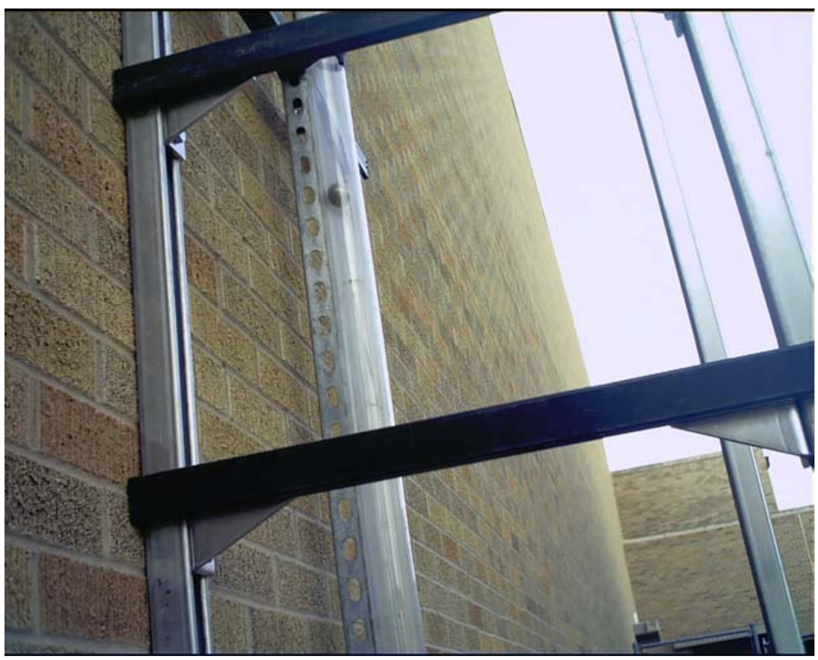


Figure A.3 - Ball Suspended in Test Facility

Appendix B
Fall Velocity Projections for the Ball, Cylinder and Ball/Cylinder

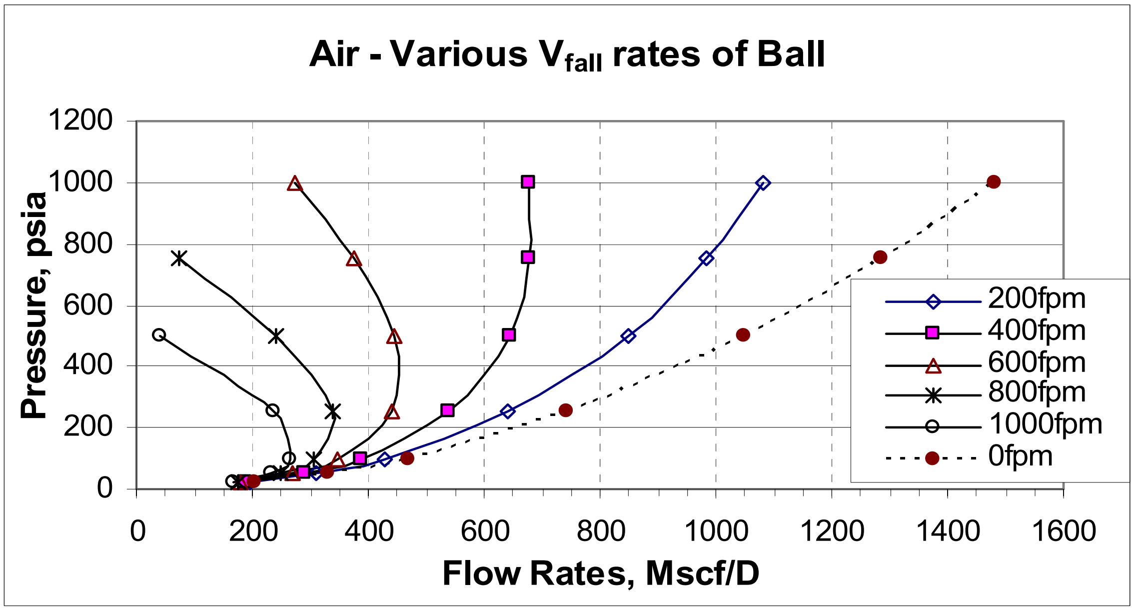


Figure B.1 - V_{fall} Rates in Air for Ball

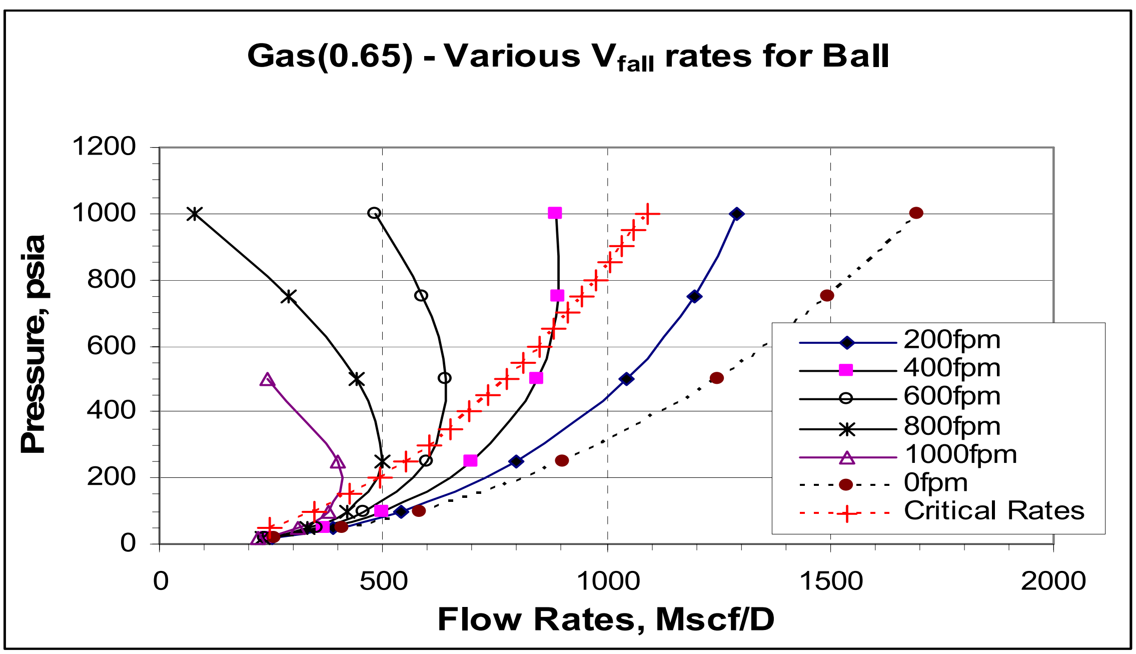


Figure B.2 - V_{fall} Rates in Gas (γ_g=0.65) for Ball

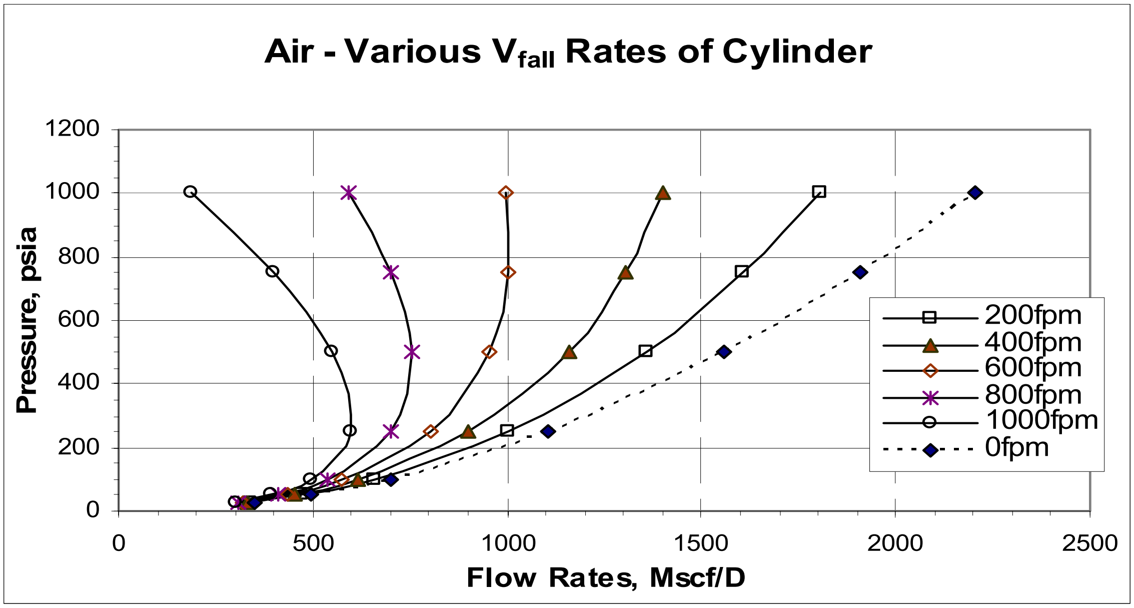


Figure B.3 - V_{fall} Rates in Air for Cylinder

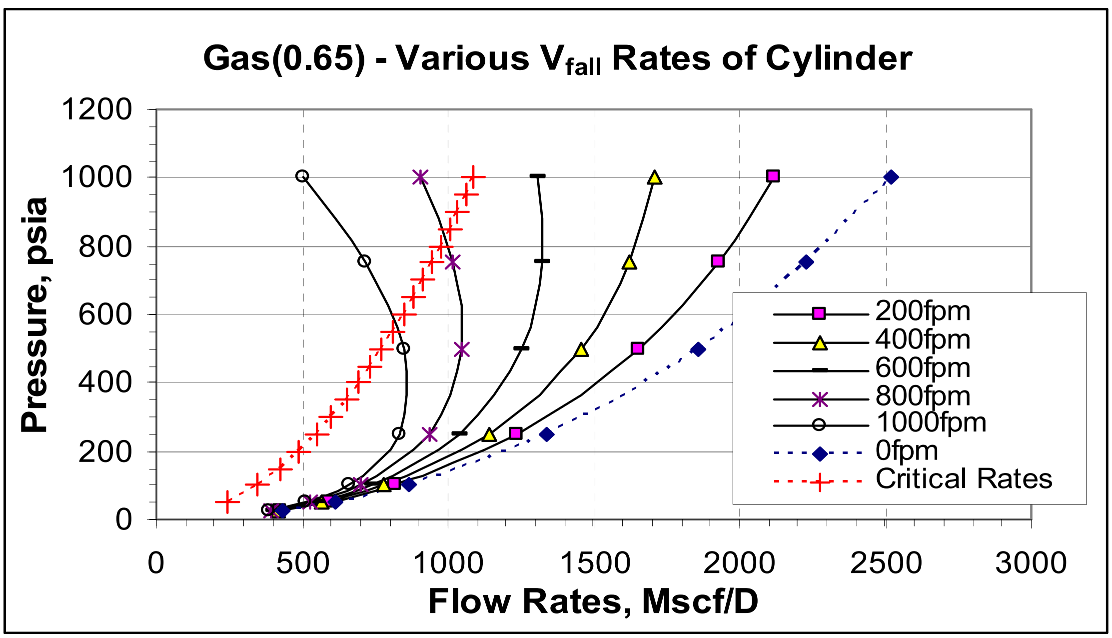


Figure B.4 - V_{fall} Rates in Gas (γ_g= 0.65 for Cylinder)

Ball:

$$\frac{(Cd)(\rho_{imp})(V_{gas}+V_{fall})^2}{2(g_c)144} = Wt / Area$$

$$V_{gas} = \left[\frac{(Wt / Area)(2)(g_c)(144}{(Cd)(\rho_{imp})}\right]^{0.5} - V_{fall}$$

Cylinder:

$$\frac{(Cd)(\rho_{imp})(V_{gas}+V_{fall})^2}{2(g_c)144} + \frac{(\rho_{drag})(f)(L)((A_{tbg})(\rho_{imp}))^2}{2(D_i^*)(g_c)(144)((A_i^* * \rho_{drag})^2} * (V_{gas}+V_{fall})^2 = 1.434 \text{ psi} = Wt / Area$$

$$A = \frac{(Cd)(\rho_{imp})}{(2)(g_c)(144)}; \qquad B = \frac{(\rho_{drag})(f)(L)((A_{tbg})(\rho_{imp}))^2}{(2)(D_i^*)(g_c)(144)((A_i^*)(\rho_{drag}))^2}$$

$$(V_{gas}+V_{fall})^2(A) + (V_{gas}+V_{fall})^2(B) = 1.43411$$

$$V_{gas}+V_{fall} = \left[\frac{1.43411}{A+B}\right]^{0.5} \ldots \text{Thus } V_{gas} = \left[\frac{1.43411}{A+B}\right]^{0.5} - V_{fall}$$

Appendix C
Calculation of the Drag Coefficients
Data and Results Collected

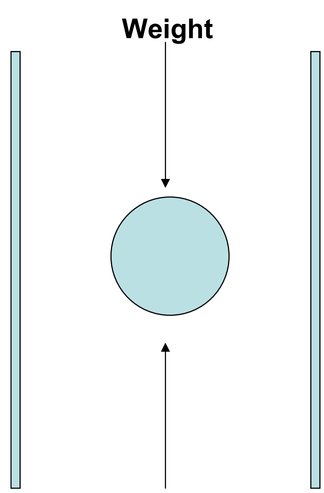
Table C1
Ball Data

Parameter	*Value*	*Units*
Diameter	0.1148	Ft
Weight	0.2176	Lbs
c/s Area	0.010357	Ft^2
Wt/Area	0.146	Psi

Table C2
Cylinder Data

Parameter	*Value*	*Units*
Outer Diameter	1.85	Inch
Inner Diameter	1.338	Inch
Thickness	0.512	Inch
Length	8.1	Inch
Weight	2.0953	Lbs
Wt/Area	1.43	Psi

Ball



$$Drag = \frac{\rho C_d A V^2}{2g}$$

Figure C.1- Schematic of Forces on Ball

$$\frac{C_d(\rho_{imp})V_{tbg}^2}{2(g_c)144} = Wt\ /\ Area\ \ldots (1)$$

Where:

$$\rho_{imp} = \frac{\frac{M_{air}}{R_g}(P_3)\gamma g}{(T_3 + 460)°\mathrm{R}\ \mathrm{Z}} = \frac{(2.7)(4.3 + 14.7)(1.0)}{(460 + 88)(1.0)} = 0.093613\ ,\mathrm{lb/ft}^3$$

$$Q_{tot} = \frac{\mathrm{Const}_{\mathrm{meter}}\ \ 24\mathrm{hr/day}\ \ 60\mathrm{min/hr}\ \ (\mathrm{P}_2 + 14.7)\mathrm{psia}}{Time_{meter-\min s} P_{atm}(T_3 + 460)°R}$$

$$= \frac{(100)(24)(60)(38.5 + 14.7)(520)}{(2.42)(14.7)(460 + 88)°R} = 204345.\ ,\mathrm{scf/D}$$

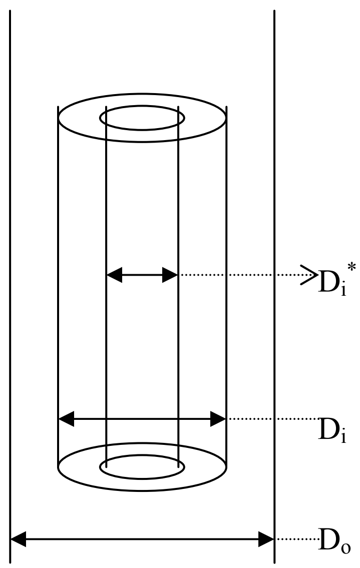
$$Q_{tbg} = \frac{Q_{tot,scfD} P_{atm} T_3 °R}{P_{3,psia} T_{sc} °R} = \frac{(204345)(14.7)(548)}{(4.3 + 14.7)(520)} = 166611.\ \ ,\mathrm{ft}^3/\mathrm{D}$$

$$V_{tbg} = \frac{Q_{tbg}}{A_{tbg}} = \frac{\frac{166611.57}{(24)(3600)}}{\frac{(\pi)(1.995)^2}{(4)(12)^2}} = 88.8\ \ ,\mathrm{ft/s}$$

Substituting in equation (1): $0.07978 * C_d = Wt\ /\ Area$

Cd $= 1.83 \ldots @\ Wt\ /\ Area = 0.146$

Cylinder



$\mathbf{D_o}$**-**$\mathbf{D_i}$ = 0.145/12 = **0.0121 ft**

$\mathbf{D_i^*}$ = Di-thk = 1.85-(2*6.5/10/2.54)
=1.3382/12 = **0.11152 ft**

$\mathbf{A_o}$ = (π/4) * ($D_o^2 - D_i^2$) = $\mathbf{3.04083*10^{-3}}$ **ft**

$\mathbf{A_i^*}$ = (π/4) * D_i^{*2} = $\mathbf{9.7678*10^{-3}}$ **ft**

Figure C.2 - Cylinder

The equation is:

$$\frac{(Q/A)_o^2}{D_o - D_i} = \frac{\left(\frac{Q_{tot} - Q_o}{A_i^*}\right)}{D_i^*}$$

Substituting the values we get,

$$94.099Q_o^2 - Q_{tot}^2 + 2Q_{tot}Q_o - Q_{tot}^2 = 0$$

$$Q_{tot} = \frac{\text{Const}_{\text{meter}}\ \ 24\text{hr/day}\ \ 60\text{min/hr}\ \ (\text{P}_2 + 14.7)\text{psia}}{Time_{meter-\min s} P_{atm} (T_3 + 460)°R} \qquad Q_{tbg} = \frac{Q_{tot,scfD} P_{atm} T_{3°R}}{P_{3,psia} T_{sc} °R}$$

$$Q_{tot} = \frac{100 * 24 * 60 * (83 + 14.7) * 520}{2.567 * 14.7 * 548} = 35378.2 \ \ \text{, scf/D}$$

$$Q_{tbg} = \frac{35378.2 * 14.7 * 548}{(10.6 + 14.7) * 520} = 216626.04 \ \ \text{, ft}^3\text{/D}$$

$Q_o = 20147.75\ ft^3/D$
$Q_i^* = 196478.29\ ft^3/D$

The equation used to calculate the **Cd** of the cylinder is
$\Delta P_{impact} + \Delta P_{drag} = Wt/Area$

$$\frac{(C_d)(\rho_{imp})(V_{tbg}^2)}{(2)(g_c)(144)} + \frac{(\rho_{drag})(f)(L)(V_i^2)}{(2)(g)(D_i^*)(144)} = Wt / Area \ \ \ldots(2)$$

where,

$$\rho_{imp} = \frac{2.7(P)\gamma g}{(T + 460)Z} = (\frac{2.7)(10.6 + 14.7)}{(460 + 88)} = 0.12465 lb / ft^3$$

$$\rho_{drag} = \frac{(2.7)(P_3 - 0.5(Wt) / Area)(\gamma g)}{(T + 460)Z} = \frac{(2.7)(10.6 - (0.5)(1.4311) + 14.7)}{(460 + 88)} = 0.121 lb / ft^3$$

$$V_{tbg} = \frac{Q_{tbg}}{A_{tbg}} = \frac{\frac{216626.04}{(24)(3600)}}{\frac{(\pi)(1.995)^2}{(4)(12)^2}} = 115.5\, ft / s$$

$$V_i^* = \frac{Q_i^*}{A_i^*} = \frac{\frac{196478.29}{(24)(3600)}}{\frac{(\pi)(0.11152)^2}{4}} = 232.78\, ft / s$$

$$\text{Re} = \frac{\rho(V_i^*)D}{\mu} = \frac{V_i^*(D)}{\eta} = \frac{232.78(0.11152)}{1.8x10^{-4} \ldots @ 88^0 F} = 144220$$

Friction Factor, $f = 0.0056 + 0.5 N_{\text{Re}}^{-0.32} = 0.01677$

From (2): Cd = 7.63 …@ Wt/Area = 1.43411

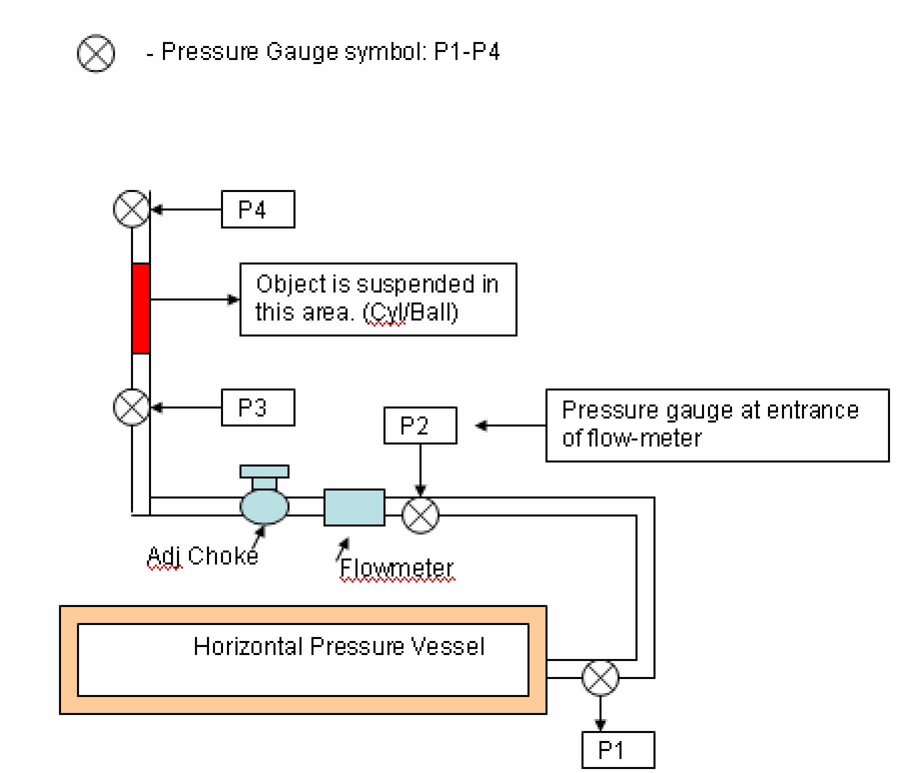


Figure C.3 - Identification of Pressure Locations

Nomenclature

Symbol	*Definition*	*Units*
A_{clr}	Clearance area between cylinder and tubing	Ft^2
A_i	Internal area of cylinder	Ft^2
A_i^*	Internal area of Cylinder	Ft^2
A_{tbg}	Area of the tubing	Ft^2
Cd	Calculated drag coefficient	-
$Const_{meter}$	Meter Constant	100 ft^3/rev
D_i	External diameter of cylinder	Ft
D_i^*	Internal diameter of cylinder	Ft
D_o	Outer diameter of cylinder	Ft
D_{tbg}	Internal diameter of tubing	in
f	Friction factor	-
g_c	Gravitational acceleration	Ft/s^2
L	Length of cylinder	Ft
M_{air}	Molecular weight of air (28.97)	Mole
P_{atm}	Atmospheric pressure	psia
P_{wh}	Wellhead pressure	psia
P_2	Pressure at flowmeter	psig
P_3	Pressure below ball, cylinder	psig
Q_i^*	Flow rate through internal diameter	
Q_{in}	Flow rate through the cylinder in tubing	ft^3/D
Q_{tbg}	Flow rate in tubing	ft^3/D
$q_{t,water}$	Critical water rate by Turner	MMscf/D
Q_{tot}	Total Flow rate through tubing	ft^3/D
R_g	Gas Constant	Psia ft^3/ lb-mole °R
T_3	Temperature at P_3	°R
T_{sc}	Temperature at standard conditions	520°R
T_{wh}	Temperature @ wellhead	°R
$Time,_{meter,min}$	Time for 100 scf through meter	Minutes
V	Velocity	Ft/s
V_{fall}	Fall velocity	Ft/s
V_{gas}	Velocity of gas	Ft/s
V_i	Velocity through cylinder	Ft/s
V_{tbg}	Velocity through tubing	Ft/s
Wt/Area	Ratio of cylinder parameters used to get the ρ_{drag}	-
z	Gas deviation factor	-
ΔP	Pressure difference across the object	Psi
μ	Viscosity	cp
ρ_{drag}	Density of air around object median	Lb/ft^3
ρ_{imp}	Density of air at impact on object	Lb/ft^3
γ_g	Gas specific gravity (air = 1.0)	-