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Supplementary Materials

Article

Revised Estimation Method for Emissions from Automated Plunger Lift Liquid Unloadings

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Method 3 Derivation

This section outlines the derivation of the version of the EPA Method 3 estimation method used for a single well with short duration venting events (<30 min). The EPA estimate in CFR 98.233 [1] is:

$$E = \sum_{p=1}^{W} \left[V_p \times \left((0.37 \times 10^{-3}) \times TD_p^2 \times WD_p \times Sp_p \right) + \sum_{q=1}^{V_p} SFR_p \times \left(HR_{p,q} - 0.5 \right) \times Z_{p,q} \right] \tag{S1}$$

where E is annual standard cubic feet (scf) of natural gas emitted, W is the total number of wells with plunger lift assist and venting for a company in a sub-basin, TD_p is the tubing diameter for each well in inches, WD_p is the tubing depth in the well to the plunger bumper in feet, SP_p is the flow line pressure in psia for the well, V_p is the annual number of unloading events for a well in a year, SFR_p is the average production rate of the well in scf/h, $HR_{p,q}$ is the hours for each venting event q that the well was left open to the atmosphere, and $Z_{p,q}$ is equal to 1 if $HR_{p,q}$ is greater than 0.5 and 0 if $HR_{p,q}$ is less than 0.5. The part of the equation before the addition sign is the volume of gas in the wellbore while the part after the addition sign describes an emissions rate at the production rate of the well if the event exceeds half an hour.

For a single well (W=1) in which all events are less than 0.5 hours, as would be expected with high venting frequency wells with plunger lift assist [2,3], the emissions per event for the well (E/V_p) would only be a function of the volume of gas in the wellbore since $Z_{p,q}$ would always be equal to zero. Thus, the Method 3 equation used in this work for high venting frequency wells with plunger lift is as follows:

$$\frac{E}{V_p} = \frac{scf}{event} = (0.37 \times 10^{-3}) \times TD_p^2 \times WD_p \times Sp_p \tag{S2}$$

Orifice Co-Efficient Derivation

The general equation for the velocity (v_0) of flow through an orifice [4] is:

$$v_0 = \frac{C_0}{\sqrt{1 - (\frac{D_0}{D_1})^4}} \sqrt{\frac{2(p_1 - p_2)}{\rho}} \tag{S3}$$

Assuming the dimensionless orifice coefficient C_0, the pipe diameter D_1, the orifice diameter D_0, and the density of the fluid ρ are constant whether the flow is for production or for venting during the liquid unloading, the ratio of the velocities between the two flow conditions would only be a function of the square root of the pressure drop across the orifice at the wellhead:

$$\frac{v_{venting}}{v_{production}} = \frac{\sqrt{(P_{shut} - P_{atm})}}{\sqrt{(P_{line} - P_{sep})}} \tag{S4}$$

where P_{shut} is the shut-in pressure to which the well builds while the plunger is dropped in psia, P_{atm} is the local atmospheric pressure and is assumed to be 14.7 psia in this study, P_{line} is the normal line pressure for the well during production in psia, and P_{sep} is the separator pressure in psia. This ratio is used to scale the duration of the venting and the gas production rate of the well to account for the increased pressure drop during venting compared to routine production activities through the separator.

Measures of Bias Used in This Work

Mean Bias (MB):

$$MB = \frac{1}{n}\sum_{i=1}^{n}(x_{predicted} - x_{measured}) \quad \text{(S5)}$$

Mean Normalized Bias (MNB):

$$\boldsymbol{MNB} = \frac{\boldsymbol{1}}{\boldsymbol{n}}\sum_{\boldsymbol{i=1}}^{\boldsymbol{n}}\frac{(\boldsymbol{x_{predicted}} - \boldsymbol{x_{measured}})}{\boldsymbol{x_{measured}}} \quad \text{(S6)}$$

Table S1. Well parameters, measured emissions data [2,3], and predictions for automated plunger lift wells used in analysis presented in this work.

Measurement Metadata from Allen et al. [2] for Automated Plunger Lift Wells							**scf Whole Gas/Event**		
Well Code	**Tubing Diameter (in)**	**Well Depth (ft)**	**Line Pressure (psig)**	**Gas Production Rate (scf/day)**	**Avg. Venting Duration (sec)**	**Methane % in Produced Gas**	**Measured in Allen et al. [2]**	**Method 3**	**Revised Method**
UBB-42-0101	2.38	6625	170	170,000	147	75.7	1207	2554	723
UBB-42-0201	2.38	6770	160	100,000	1208	78.7	10954	2468	3490
UBB-42-0401	2.38	4416	210	200,000	389	81.9	78	2074	2263
UBB-42-0501	2.38	6893	135	140,000	130	82.9	795	2154	523
UBB-42-0601	2.38	4600	135	140,000	1208	83.4	8727	1437	4862
UBB-42-0701	2.38	5061	148	170,000	276	81.1	127	1720	1353
UBB-42-0801	2.38	4782	155	155,000	433	80.5	2106	1694	1937
UBB-42-1001	2.38	7630	102	162,000	36	91.5	228	1863	166
UBB-42-1101	2.38	6756	175	175,000	262	80	1918	2675	1328
UBB-42-1201	2.38	6696	95	90,000	617	80.4	760	1533	1576
UBB-43-0101	2.38	6689	165	180,000	177	78.5	1651	2509	921

UBB-43-0301	2.38	6695	190	190,000	137	81.7	78	2860	755
UBB-50-2601	2.00	3310	12	54,000	317	76.8	1191	132	406
UBB-50-2701	2.00	3247	13	47,000	849	77.7	2571	130	949
UBB-50-2801	2.00	2935	12	32,000	33	78.2	72	116	25
UBB-50-2901	2.00	2786	15	15,000	90	83	1196	121	33
UBB-50-3001	2.00	2455	26	26,000	692	81.9	289	145	465
UBB-50-3101	2.00	3067	13	46,000	73	80.6	72	125	80
UBB-50-3201	2.00	3087	12	46,000	309	76.6	1730	121	336
UEF-49-0501	2.38	8783	70	18,000	123	82.4	519	1553	62
UEY-41-0101	2.38	4174	62	38,000	400	97.8	319	668	422
UEY-41-0201	2.38	4402	7	90,000	274	97.8	132	199	543
UEY-41-0301	2.38	5038	25	129,000	191	97.8	220	417	636
UEY-41-0401	2.38	4098	93	107,000	206	97.8	561	921	625

References

1. Electronic Code of Federal Regulations, Title 40: Protection of Environment, Part 98: Mandatory Greenhouse Gas Reporting, Subpart W: Petroleum and Natural Gas Systems. Available online: https://www.ecfr.gov/cgi-bin/text-idx?SID=555cd31d46a2d3217eeb4b4e3ec4571a&mc=true&node =sp40.23.98.w&rgn=div6 (accessed on 30 December 2019).
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4. Geankoplis, C.J. *Transport Processes and Separation Process Principles*, 4th ed.; Prentice Hall: New Jersey, NJ, USA, 2007; p. 40.