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Multiday Measurements of Pneumatic Controller Emissions Reveal the Frequency of Abnormal Emissions Behavior at Natural Gas Gathering Stations

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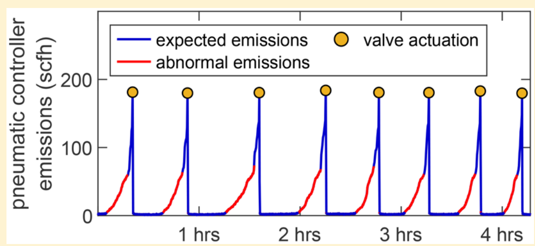
ABSTRACT: Gas-driven pneumatic controllers (PCs) and actuators used in all natural gas sectors vent uncombusted natural gas to the atmosphere during operation and contribute approximately 20% of methane emissions from the natural gas supply chain. In this study, multiday measurements were utilized to better characterize PC emission rate profiles. Emissions from 72 PCs were successfully measured at 16 gathering compressor stations for an average of 76 h each between June 2017 and May 2018. These measurements are the first known multiday recordings of emissions of PCs *in situ* at operating natural gas facilities.



These measurements revealed previously unidentified emissions behaviors. A review by an expert panel identified 30 PCs (42% of measured devices) that exhibited abnormal emissions behavior, including 25 of 40 intermittent-vent PCs, 5 of 24 low-bleed PCs, and 0 of 8 high-bleed PCs measured. Abnormally operating PCs had emissions substantially higher than the emissions of those operating normally. For intermittent-vent PCs, abnormally operating PCs showed average emission rates of 16.1 standard $ft^3\ h^{-1}$ (scfh, whole gas) versus 2.82 scfh for normally operating PCs. Sampling simulations also indicate that measurements of ≥24 h are necessary to quantify emissions to within 20% [11−31%] of a PC's long-term average emissions. Due to potential biases in sample size and diversity and corrections for measurement errors, we recommend these data be utilized for only a qualitative understanding of PC behavior and not for developing emission factors.

INTRODUCTION

Advances in hydraulic fracturing have led to a boom in natural gas production worldwide. Between 2000 and 2017, U.S. annual dry natural gas production increased by 40% to 26.9 trillion standard ft^3 (scf).[1] The combustion of natural gas produces less carbon dioxide (CO_2) than the combustion of other fossil fuels, making it an attractive option for reducing greenhouse gas (GHG) emissions from power generation and transportation. However, because uncombusted methane (CH_4) has a global warming potential 32 times greater than that of CO_2 on a 100 year time scale and 86 times greater than that of CO_2 on a 20 year time scale,[2] increasing supply chain throughput has increased attention on GHG contributions from accidental and operational releases of CH_4 from natural gas infrastructure.

Automated, pneumatically actuated valves are used to control processes (liquid level, temperature, gas flow, and pressure) in all sectors of the natural gas industry. Isolation or emergency shutdown valves, and liquid or chemical injection pumps, may also be controlled and actuated pneumatically. Many of these process-control systems use natural gas to power actuators because gathering stations have a continuous source of high-pressure natural gas, eliminating the need for electrical power on remote sites or separate compression equipment to compress and dry ambient air. Each pneumatically actuated valve has a dedicated controller that monitors a process variable and operates the valve to maintain the variable within desired limits. These pneumatic controllers (PCs) vent natural gas to the atmosphere during their normal operation. In 2016, PCs were estimated to emit 1257 Gg of CH_4, approximately 20% of all CH_4 emissions from onshore natural gas operations.[3]

The U.S. Environmental Protection Agency (EPA) classifies PCs according to their venting behavior as intermittent or continuous bleed.[3] Continuous bleed devices are further

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classified as low-bleed, which vent <6 scfh (standard cubic feet per hour), or high-bleed, which vent ≥6 scfh, based on designed steady state emission rates.[4] In addition to emissions vented during normal process-control operation, PCs may also emit gas through leaking or abnormally operating controller components.

Studies since the 1990s have estimated emissions from PCs at oil and gas production sites, using direct measurements[5−7] or engineering calculations. In general, studies combining direct measurements with engineering calculations, or relying on engineering calculations alone, report average emission rates lower than those of studies relying entirely on direct measurements.[8−12] This discrepancy has been attributed to the difficulty of representing abnormally operating PCs, or PCs emitting at higher rates than designed, in engineering calculations, possibly indicating that abnormally operating PCs have a disproportionate impact on average emission rates. In addition, methods utilized for direct measurements of PC emissions have entirely relied on measurement durations of ≤1 h, with the majority of measurements being <15 min. Because short-duration measurements may capture few, if any, actuations of intermittent controllers, studies must make assumptions regarding both actuation frequency and emission rates during actuations. These assumptions have two impacts. First, they increase uncertainties in estimating actuation emissions during normal operations, and second, abnormal actuation behavior is not characterized, and typically not included, in either measurements or assumptions for devices that were not observed to actuate during measurement. For both inventory and reporting program applications in most sectors, the EPA utilizes PC emission factors derived from a small number of short-duration measurements made on production sites prior to 1996.[13] These factors may be out of date due changes in the design and mix of PCs in use, differences between natural gas sectors, and changes in operational practices since the 1990s.

PCs have been the focus of multiple regulatory changes in the past two years, including new national regulations and reporting requirements. Regulators in Colorado are conducting a study of PCs that may impact emission regulations in multiple states.[14] The high level of interest in PC emissions evidenced by these actions is driven by concerns that PC emissions may be underestimated in inventories and also by a belief that operational changes could reduce PC emissions at relatively low cost. In both cases, the emissions behavior documented in this study provides substantial new information critical to these discussions.

■ MATERIALS AND METHODS

Station Selection. The PC emissions data presented in this paper were collected as part of a larger gathering emission factor (GEF) field campaign, which focused on developing CH_4 emission and activity factors for gathering compressor stations in the United States. Nine midstream natural gas companies acted as industry partners in this study, offered access to their stations, and provided input on methods and analysis (section S1-1[15]).

Measurements for this study were performed in two phases: (1) at the random selection of compressor stations identified for GEF study and (2) by guided station selection after the main field campaign. A nationally representative sample of stations was drawn from industry partner compressor stations using a randomized, clustered sampling strategy that did not emphasize selecting stations that utilized natural gas-driven PCs. This selection of stations was visited over 11 weeks during the GEF study, with PC emissions measurements scheduled at one station per week. However, because 27% of partner stations utilized compressed air to power pneumatic control systems, there were several weeks when long-duration PC measurements could not be performed; i.e., there were no gas pneumatics to measure. Emission measurements were made on 28 PCs at six stations between June and November 2017 during this phase of the study (section S1-2.1[15]).

To increase sample size and diversity, the study team continued PC emission measurements after completion of the GEF field campaign. A secondary sample of stations was selected in collaboration with industry partners in geographic areas not visited during the GEF field campaign (i.e., guided rather than random selection). During this phase, measurements were made on an additional 44 PCs at 10 gathering stations between November 2017 and May 2018. In total, PC measurements were made at stations owned by eight of nine partner companies; all stations operated by the last partner utilized compressed air for pneumatic controls (section S1-2.2[15]).

Measurement Equipment. Six measurement units were utilized to record PC emissions, each of which included a thermal mass flow meter, a portable power supply, and a data logger. Flow meters were directly connected in line to PCs' pressurized gas supply lines or to PCs' exhaust vent ports using flexible tubing. Power supplies allowed for an average measurement duration of 76 h, during which the emission rate, gas temperature, and gas pressure were recorded to the unit's data logger at a 1 Hz sampling rate. Units were left unattended on facilities for approximately 3 days, so all components were rated for environments where explosive gases are present during normal operation (class I/division I) or were housed in explosion-proof enclosures (section S1-3[15]).

Pneumatic Controller Selection for Measurement. The focus of this study was to measure emissions from PCs actively controlling station temperature, level, and pressure processes. Due to the limited number of PCs that could be measured on each station, emissions from pneumatic emergency shutdown, isolation, and pump devices were not measured in this study as these devices do not actively control process variables. Selection was also constrained by site operation and safety because a PC's supply gas lines must be temporarily disconnected during meter installation. While on/off controllers can be disconnected without disturbing the controlled process, PCs designed to continuously throttle or maintain sensitive processes cannot be disconnected without disturbing equipment operation. In these cases, portions of the station were isolated and depressurized before installation, or flow meters were connected to PC exhaust ports. If these options were not available, the PC could not be measured. Due to these constraints, PCs could not be randomly selected for measurement. Instead, the study team instrumented a representative sample of PCs at each site visited. PCs were selected for measurement on an opportunistic basis, guided to maximize the sample diversity of PC models, vent behavior, and control applications throughout the study. The final sample distribution in this study, stratified by EPA type (33% low-bleed, 11% high-bleed, and 56% intermittent-vent), is comparable to EPA count estimates of PCs on gathering stations (23% low-bleed, 5% high-bleed, and 72% intermittent-vent) (section S1-3.3[15]).

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Table 1. Average Emission Rates for Normally and Abnormally Operating PCs

pneumatic controller type	no. of samples		average emissions (scfh whole gas)	
	total	exhibiting abnormal behavior[a]	normally operating	behaving abnormally[a]
intermittent	40	25	2.82 [+3.23/−2.41]	16.11 [+7.88/−6.35]
low-bleed	24	5	0.68 [+0.50/−0.42]	34 [+20.81/−19.78]
high-bleed	8	0	19.25 [+13.55/−10.26]	–[b]
total	72	30	4.98 [+3.49/−2.95]	19.09 [+7.61/−6.80]

[a]An expert panel identified abnormal emissions behavior from the pneumatic controller. [b]No high-bleed PCs were assigned as malfunctioning.

Postcampaign Analysis. At the end of the field campaign, we discovered a meter behavior in which the flow meters indicated a non-zero (NZ) flow reading when meters were pressurized and no flow was occurring. The magnitude of the NZ value was observed to increase with increasing gas supply pressure and was not present for supply pressures of <30 psia. Therefore, meters attached to PC exhaust ports, and those attached to supply gas lines operating at pressures of <30 psia, did not exhibit this error; meters attached to supply gas lines with pressures of >30 psia exhibit this error to varying degrees. Laboratory tests were performed to establish pressure thresholds above which each meter could indicate a NZ flow under no-flow conditions, and meter-specific correction factors were applied to 42% of PC data sets (section S1-4.2.1[15]). After analysis, 14 data sets from the original sample set of 86 were discarded because they were heavily impacted by this error and did not show recordings that were distinguishable from noise (section S1-4.4[15]). Because the meters were calibrated on ambient air, data were also corrected for the natural gas compositions at each station (section S1-4.1[15]). While these corrections impacted the average emission rates for effected data sets, they did not obscure the overall emissions behavior. However, because the NZ corrections impacted PC types unevenly and obscure potential emission behavior below the NZ threshold, we recommend that these data be utilized for only a qualitative understanding of PC behavior and not for developing emission factors for PCs or other regulatory purposes.

Postcampaign, a panel of four industry experts and three study team members reviewed data sheets, specifications, and recorded data for each PC evaluated (section S1-5[15]). The review panel confirmed classifications of each PC according to EPA categories based on the PC's application, supply pressure, information gathered from station operators, and manufacturer published specifications (section S1-5.1[15]). The panel also determined if each PC's emission behavior was consistent with the device's design and intended operation, identified common failure modes across the sample of PCs with abnormal emissions behavior, and provided perspectives on possible causes of the irregular emissions patterns observed (section S1-5.2[15]). PCs were assigned as abnormally operating strictly on the basis of the emissions behavior of the device. By this definition, a device identified as abnormally operating could still be performing its intended process-control function but shows an emission rate or pattern that is inconsistent with the design and installation of the PC.

■ RESULTS AND DISCUSSION

Overall Emissions Behavior. The review panel established four criteria for identifying abnormal emission behavior for intermittent-vent PCs: (1) extended ramp up in emissions prior to actuation events, (2) continuous emissions or lack of distinct actuation events, (3) emissions not returning to zero between actuation events, and (4) other irregular behavior. Low-bleed PCs were classified as abnormally operating if average emissions exceeded 6 scfh, and high-bleed PCs were classified as abnormally operating if emissions exceeded manufacturer's specifications (section S1-5.2[15]). Using these criteria, 42% (30 of 72) of the evaluated PCs were classified as abnormally operating while 73% of measured emissions were attributed to those PCs. Differences in average emission rates are pronounced, with abnormally operating intermittent PCs exhibiting 5-fold greater emissions than those classified as normally operating and low-bleed PCs 50-fold greater emissions (albeit on a small sample size) than those classified as normally operating (Table 1).

Previous studies[5−9,16] have reported a "long-tailed" distribution in which a majority of total emissions are attributed to a small subset of PCs. While a long-tailed distribution was observed in this study, the skew was not as pronounced as in other studies; for this study, 95% of the emissions are attributed to the highest-emitting 42% of devices, compared with the same fraction of emissions from the highest-emitting 19% of devices in the study of Allen et al.[9] A possible cause of the difference is the longer measurement duration in this study; many PCs measured during previous studies exhibited no emissions (e.g., intermittent-vent PCs that did not actuate), or high-emitting behavior may have not occurred during shorter measurement periods used in prior studies. However, this disagreement could also be due to operational or equipment differences between PCs installed on production well pads versus gathering stations.

Low-Bleed PCs. The five low-bleed PCs of 24 total that were classified as abnormally operating (Table 1) exhibited emissions continually exceeding the 6 scfh threshold for the entire duration of the measurement period. While there is some evidence that a high supply pressure may have contributed to high emissions [four of the five (J-6, J-2, D-3, and J-4) were connected to the highest supply gas pressures recorded for low-bleed controllers], the number of samples is too small to make any conclusive statements (Figures S1-24[15]).

Intermittent-Vent PCs. Twenty-five of 40 intermittent-vent PCs (62.5%) exhibited abnormal operating behavior at some point during the measurement period. Given the operating characteristic of intermittent-vent PCs, emissions during normal and abnormal operating periods can be isolated, as summarized in Figure 1. Of the 25 abnormally operating intermittent-vent PCs, 16 had periods during their observation time when they were operating correctly.

Normally operating emission conditions were determined by identifying actuations, i.e., peaks in emission traces, and considering all emissions for 3 min before and the 5 s after each peak as normal emissions, based upon the expert panel's understanding of actuation times for normally operating devices. All other emissions outside of this time window

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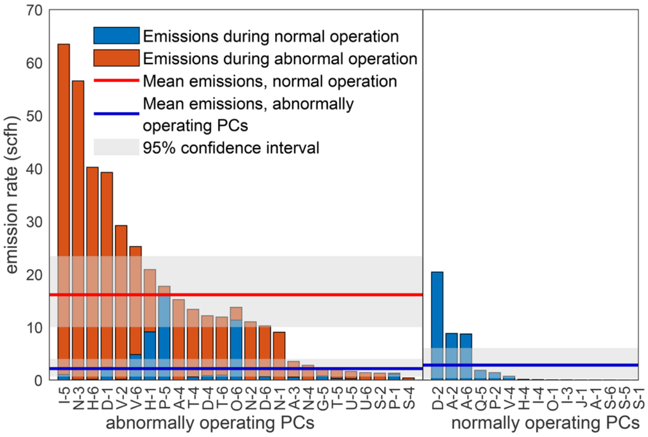

Figure 1. Emissions for intermittent-vent pneumatic controllers. Emissions during abnormal operations were separated from normal emissions by isolating individual actuations of the controller (see the text). Most abnormally operating controllers exhibited periods of normal operations, during which emissions were similar to those of normally operating controllers. However, mean total emissions from abnormally operating controllers are 5 times higher than emissions from controllers exhibiting only normal operations.

were classified as abnormal emissions (Figure S1-22[15]). The average emission rate for the 25 abnormally operating controllers is 16.11 [+7.88/−6.35] scfh. If the emissions during abnormal operating periods are removed, the average emissions for these controllers is 2.15 [+1.89/−1.38] scfh, which is comparable to average emissions from the 15 normally operating intermittent-vent PCs (2.82 [+3.23/−2.41] scfh). These data indicate that emissions during normal operating conditions for both normally and abnormally operating intermittent-vent PCs are similar.

Impact of Measurement Duration. All previous studies known to the authors measured emissions from PCs using measurement times of 15−60 min. Several of these studies[9,11,12] acknowledge the difficulty in accurately characterizing emission rates with short measurement periods, given the high-temporal variability PC operation. To better understand the impact of measurement duration on observed average emission rates, the short measurement durations of previous studies were simulated using the long-duration measurements collected in this study. The simulation drew 1000 random, 15 min, samples from measurements recorded between 8 a.m. and 5 p.m. This simulation is equivalent to "walking up to a PC and taking a 15 min sample" during any daytime 15 min period.

Our recordings show that both the emissions rate and the actuation frequency of intermittent-vent PCs vary widely during the three-day measurement duration. If a measurement is made during any randomly selected 15 min period, there is a low probability that the actuations occurring during that sample will be representative of the actuation rate over an extended period. For both high- and low-bleed continuous vent PCs, emissions rates vary less over time than those of intermittent-vent devices. Therefore, 15 min duration measurements are more representative of long-term averages for these PC types (Figure S1-23[15]).

Assuming that the mix of controller types, and the mix of normally and abnormally operating PCs, seen here is representative of a larger population of controllers, this simulated sampling strategy can be extended to longer time durations to determine the minimum measurement duration required to characterize average emissions for each device or any set of devices, to a desired accuracy. For the mix of PCs measured here, the average expected absolute error of a 15 min measurement is 49% [31−71%]. If the measurement duration is extended to 24 h, the expected absolute measurement error is reduced to 20% [11−31%] (Figure 2).

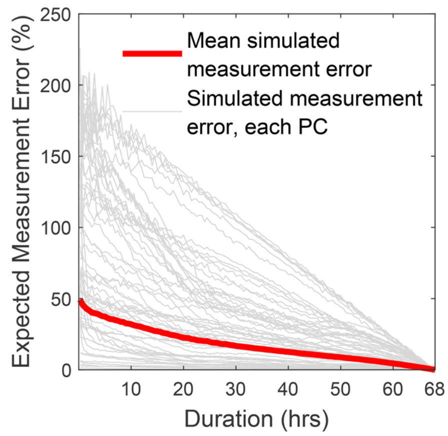

Figure 2. Simulated measurement error of the 61 PC emission recordings with durations of ≥68 h. Each PC is shown as one line on the plot, with the line intensity indicating average emissions from the PC for the full 68 h period. The mean error for all 61 controllers is shown as the overlaid red line. The measurement error for each duration was simulated by randomly selecting 1000 contiguous subsamples from the long-duration data set and comparing the sampled emission rate to the long-duration average emission rate.

Operational Impacts. These PC emission measurements highlight previously unidentified behaviors of pneumatic controllers, including a high fraction of abnormally operating devices and unreported emission patterns indicative of abnormal operations. These observations suggest a need to use longer-duration, direct measurements to develop emission factors for use in inventories and reporting programs as well as for programs seeking to identify high-emission or abnormally operating intermittent-vent PCs. Data suggest that short measurement times are unlikely to identify abnormally operating intermittent-vent PCs. While these short observations would detect continuous-bleed PC emissions, it would be difficult to identify PCs emitting at higher than specified rates without quantifying identified emissions.

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Notes

The authors declare no competing financial interest.

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