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Original Research

Monitoring and Investigating Methane Leakage in Coal Gas Production

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Abstract

The Qinshui Basin in Shanxi Province in northern China is currently the largest production area of coal bed methane (CBM) in China. For this study, methane (CH_4) measurements were collected from 113 wellheads to determine primary gas leakage locations. The results indicate that the leakage is primarily from water outlets and tubing; three leakage points accounted for 95.79% of the total measured gas. With respect to measurement variability, the standard deviation for gas measurements of the tubing was the largest at 12.28. Wells with good geological conditions and scientific management exhibited very low leakage. In contrast, wells with unfavorable geological conditions and improper management had much higher leakage values. The standard deviation of leakage at the water outlets was the next lowest. The role of different processes and running states had the greatest role in CH_4 leakage. The leakage from horizontal wellheads was the highest, with an average rate of 20.80 l/min, compared to the average of leakage from flowing wells at 0.88 l/min; this is far below that of the wells that used mechanical gas pumping. The overall emission factor of the 113 examined wells was 176 kg CO_2-e t^{-1}, which was far greater than the previously reported Australian emission level (11.7 kg CO_2-e t^{-1}).

Keywords: coal bed methane, leakage, methane, emission factor

Introduction

Coal bed gas (CBG) refers to a form of gas that exists in coal seams. It is mainly composed of methane (also referred to as coal bed methane or CBM). The gas is absorbed on the surface of the coal matrix; part of it dissociates from coal pores within the coal, while part of it dissolves into hydrocarbon gas in coal bed water [1, 2]. Coal bed gas is an important energy resource because of the increasing demand for gas as a substitute for coal and oil in generating electricity [3].

Coal bed methane resources in China are abundant; the volume of this geological resource in China is surpassed only by Russia and Canada [4]. CBM industry development is important to improve the energy production-consumption structure and work safety conditions of coal mining activities. Also, CBM is important for relieving the current shortage in China's natural gas supply [5].

As Fig. 1 shows, there are nine major CBM basins in China: Odors, Qinshui, Junggar, Diandongqianxi, Erlian, Tuha, Tarim, Tianshan, and Hailaer. Each basin has a geological reserve of more than 1x10^{12} m^3 with a total

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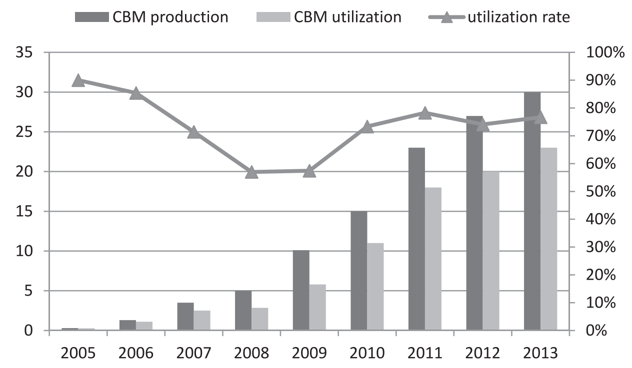

Fig. 1. The development and utilization of CBM in China.

reserve of 30.9 Tm^3. This represents 84% of the total CBM resources in China [6].

CMB development in China has increased significantly over the past decade (Fig. 2). Until 2005, China's CBM production was 3x10^8 m^3 (Fig. 1); after this, production increased to 300x10^8 m^3. This increased production mainly occurred in Shanxi province, where local production was 287x10^8 m^3. This represents 95.7% of the total production in China. In 2013, this percentage increased to 99%, with an average annual growth rate of 77.6%.

A major environmental impact of the CMB industry is methane emissions. Methane is recognized as a greenhouse gas (GHG) that likely plays a role in global warming. Methane traps heat in the atmosphere more effectively than carbon dioxide by a factor of 20 or more [7, 8]. The CBM utilization rate is currently no more than 80% in China, an increase from 76.7% in 2013. Therefore, analyzing sources of CH_4 leakage and reducing these leakages during the CBM development process is vital to maximize resource use with respect to energy, economic, and environmental concerns.

With the rapid development of the unconventional gas industry, research on methane leakage is emerging as a study area [9-11]; however, we have identified only two studies that have focused on leakage in CBM development. Recently, researchers in Australia measured unintended (or fugitive) emissions from equipment and well casings in Australian CBM production facilities. United States researchers used a top-down method at the field scale, collecting total atmospheric measurements and then attributing these to sources. This research found discrepancies with the bottom-up estimates. However, considering these countries' differences in geological conditions and technology systems, study results may have limited application to China.

The site for this study, the Qinshui Basin of Shanxi Province in northern China, is currently the largest production base for CBM in China. Methane measurements of 113 wellheads were performed to assess leakage conditions and contributing factors. First, leakage conditions and related factors of different sources were analyzed. Secondly, CH_4 leakage from different production technologies and running states were compared. Finally, the comprehensive CH_4 leakage rate of the CBM wells was analyzed and the leakage factor estimated.

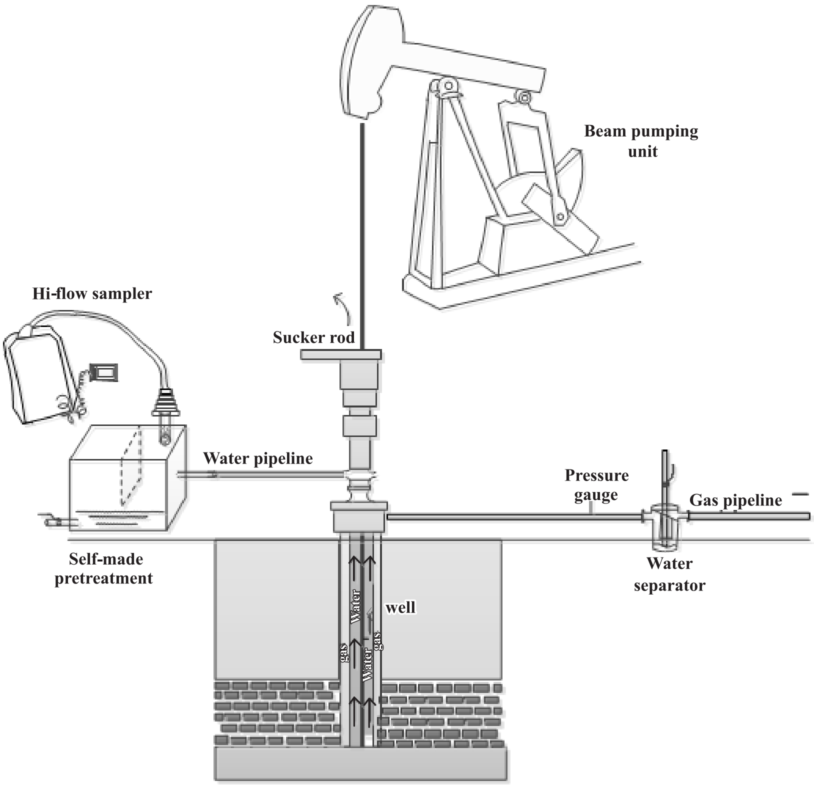

Fig. 2. System boundary of this study.

Table 1. The basic situation of 113 wells.

Number	Name	Block	Gas production m³/d	Technological types	Running state
1	YH-97	YH block	11,830	Vertical well	pumping
2	SHx-291	YH block	2,810	Vertical well	pumping
3	SHx-292	YH block	2,693	Vertical well	pumping
4	YH-51	YH block	4,544	Vertical well	pumping
5	YH-54	YH block	800	Vertical well	pumping
6	YH-036	YH block	4,512	Vertical well	pumping
7	YH-100	YH block	101	Vertical well	pumping
8	JNP01-2	YH block	3,792	Horizontal well	pumping
9	YH-054-1	YH block	1,440	Vertical well	pumping
10	YH-99	YH block	6,144	Vertical well	pumping
11	YH-29	YH block	2,652	Vertical well	pumping
12	YH-023	YH block	9,288	Vertical well	pumping
13	YH-026	YH block	8,802	Vertical well	pumping
14	YH-011	YH block	5,404	Vertical well	pumping
15	YH-010	YH block	3,144	Vertical well	pumping
16	YH-006	YH block	4,800	Vertical well	pumping
17	YH-007	YH block	141	Vertical well	pumping
18	YH-13-04	YH block	0	Vertical well	pumping
19	YH-13-01	YH block	0	Vertical well	pumping
20	YH-13-18	YH block	0	Vertical well	pumping
21	JS-14	YH block	0	Vertical well	pumping
22	JS-055	YH block	50	Vertical well	pumping
23	JS-056	YH block	3,216	Vertical well	Flowing
24	JS-100	YH block	2,832	Vertical well	pumping
25	JS-58	YH block	6,720	Vertical well	pumping
26	JS-050	YH block	163	Vertical well	Flowing
27	JS-051	YH block	2,352	Vertical well	pumping
28	JS-49	YH block	150	Vertical well	pumping
29	SHx-161	YH block	2,643	Vertical well	Flowing
30	JS-052	YH block	65	Vertical well	pumping
31	JS-165	YH block	2,176	Vertical well	pumping
32	JS-048	YH block	3,056	Vertical well	pumping
33	ZH-62	ZH block	1,440	Vertical well	pumping
34	ZH-57	ZH block	1,608	Vertical well	Flowing
35	ZH-009-4	ZH block	360	Cluster well	pumping
36	ZH-009-3	ZH block	336	Cluster well	pumping
37	ZH-009-2	ZH block	624	Cluster well	pumping
38	ZH-50-4	ZH block	120	Cluster well	pumping
39	ZH-50-3	ZH block	192	Cluster well	pumping

Table 1. Continued.

40	ZH-50-2	ZH block	240	Cluster well	pumping
41	ZH-50-1	ZH block	120	Cluster well	pumping
42	ZH-88	ZH block	2,456	Vertical well	pumping
43	ZH-119	ZH block	2,880	Vertical well	pumping
44	ZH-103	ZH block	384	Vertical well	pumping
45	ZH-120	ZH block	888	Vertical well	pumping
46	ZH-137	ZH block	1,200	Vertical well	pumping
47	ZH-104	ZH block	1,104	Vertical well	pumping
48	ZH-122	ZH block	720	Vertical well	pumping
49	ZH-105	ZH block	1,248	Vertical well	pumping
50	ZH-91	ZH block	96	Vertical well	pumping
51	ZH-92	ZH block	4,416	Vertical well	pumping
52	ZH-214	ZH block	50	Vertical well	pumping
53	ZH-182	ZH block	336	Vertical well	pumping
54	ZH-181	ZH block	312	Vertical well	pumping
55	ZH-193	ZH block	624	Vertical well	pumping
56	ZH-192	ZH block	1,080	Vertical well	pumping
57	ZH-179	ZH block	1,896	Vertical well	pumping
58	ZH-453	ZH block	0	Vertical well	pumping
59	ZH-191	ZH block	288	Vertical well	pumping
60	ZH-178	ZH block	504	Vertical well	pumping
61	ZH-166	ZH block	504	Vertical well	pumping
62	ZH-169	ZH block	48	Vertical well	pumping
63	ZH-168	ZH block	48	Vertical well	pumping
64	ZH-156	ZH block	0	Vertical well	pumping
65	ZH-149	ZH block	240	Vertical well	pumping
66	ZH-161	ZH block	0	Vertical well	pumping
67	ZH-148	ZH block	0	Vertical well	pumping
68	ZH-159	ZH block	0	Vertical well	pumping
69	ZH-145	ZH block	0	Vertical well	pumping
70	ZH-128	ZH block	504	Vertical well	pumping
71	ZH-144	ZH block	984	Vertical well	pumping
72	ZH-153	ZH block	768	Vertical well	pumping
73	ZH-142	ZH block	240	Vertical well	pumping
74	ZH-126	ZH block	0	Vertical well	pumping
75	HD-114	HD block	1,668	Vertical well	pumping
76	HD-101	HD block	3,445	Vertical well	Flowing
77	HD-096	HD block	2,239	Vertical well	pumping
78	HD-88	HD block	2,568	Vertical well	pumping
79	HD-082	HD block	4,614	Vertical well	pumping
80	HD-090	HD block	563	Vertical well	pumping

Table 1. Continued.

81	HD-083	HD block	4,548	Vertical well	pumping
82	HD-070	HD block	662	Vertical well	pumping
83	HD-063	HD block	552	Vertical well	pumping
84	HD-055	HD block	3,018	Vertical well	pumping
85	HD-270	HD block	4,257	Vertical well	pumping
86	HD-060	HD block	1,358	Vertical well	pumping
87	HD-065	HD block	1,128	Vertical well	pumping
88	HD-144	HD block	7,488	Vertical well	pumping
89	HD-155	HD block	5,304	Vertical well	pumping
90	HD-145	HD block	552	Vertical well	pumping
91	HD-138	HD block	552	Vertical well	pumping
92	HD-254	HD block	2,256	Vertical well	pumping
93	HD-080	HD block	552	Vertical well	pumping
94	HD-079	HD block	2,616	Vertical well	pumping
95	HD-156	HD block	504	Vertical well	pumping
96	HD-086	HD block	672	Vertical well	pumping
97	HD-084	HD block	1,824	Vertical well	pumping
98	HD-168	HD block	1,920	Vertical well	pumping
99	HD-167	HD block	2,808	Vertical well	pumping
100	HD-153	HD block	408	Vertical well	pumping
101	HD-180	HD block	1,104	Vertical well	pumping
102	HD-203	HD block	1,152	Vertical well	pumping
103	HD-202	HD block	504	Vertical well	pumping
104	HD-201	HD block	1,032	Vertical well	pumping
105	HD-281	HD block	1,632	Vertical well	pumping
106	HD-092	HD block	1,656	Vertical well	pumping
107	HD-188-2	HD block	240	Vertical well	pumping
108	HD-085	HD block	1,680	Vertical well	pumping
109	HD-260	HD block	1,488	Vertical well	pumping
110	HD-226	HD block	1,056	Vertical well	pumping
111	HD-225	HD block	2,760	Vertical well	pumping
112	HD-241	HD block	0	Vertical well	pumping
113	HD-240	HD block	408	Vertical well	pumping

Experimental Methods

Well Selection

This study selected 113 wells and took into account geological conditions, production technologies, running states, and gas production rates. Three different blocks (YH, ZH, and HD), were randomly selected to compare different geological conditions. Production technologies included vertical, cluster, and horizontal wells. Running states took into account flowing wells and regular pumping wells. Well production rates are provided in Table 1.

System Boundary

This research study focused on the well pad at each sampling site, including the area around the wellhead (usually fenced) that contains the surface equipment

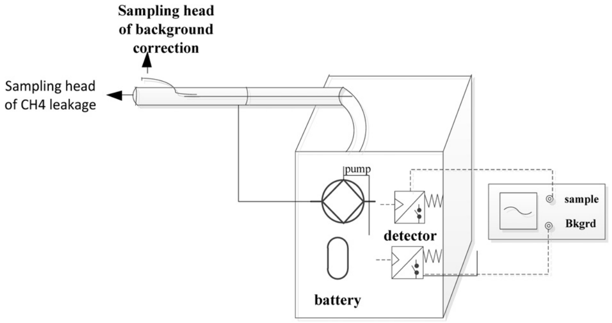

Fig. 3. Work flow of the Hi Flow Sampler.

associated with CBM production. This includes the tubing, water outlet, flange, sealing, connection, and other components. Leakage from these components can occur in several ways. First, methane leakage from tubing is caused by the abrasion of sucker rod and tubing strings. Second, leakage through water outlets is caused when the gas pressure is too high, resulting in CBM dissolution into the water in a super-saturated state. This situation causes the CBM to be drawn into the oil tubing, where the imbalance of pressure inside and outside the tubing will release a portion of the CBM. Third, other leakage may result from sealing problems in the flanges, seals, connections, valves, and other components.

Monitoring CH_4 Leakage from Tubing

CH_4 leakage from tubing was measured using a Hi Flow Sampler during normal operating conditions. The sampler was deployed as close to the leak point as possible, normally less than 10 cm. The monitoring time was 2 to 10 min and the detection range was 1.42 l/min to 226 l/min. Fig. 3 shows the measuring procedure.

First, air around the leak point was pumped into the sampler using a negative pressure pump. A Venturi meter measured gas flow. Then the gas was fed into a catalytic combustor, where an ion flow was produced by organic gas combustion. The methane concentration was then measured by examining the ion flow using a flame ionization detector (FID).

An ambient background air sample was collected around each examined well during the sampling event to assess background levels of methane. Leakage was calculated using the following equation:

$$M = (S_1 - S_0) / t$$

…where M (l/min) is methane leakage, S_1 (l) is methane leakage at the leak point, S_0 (l) is the background methane level, and T (min) is the monitoring time.

Monitoring CH_4 Leakage from Water Outlet

A pretreatment device was constructed to prevent droplets and ashes from entering the Hi Flow Sampler. The device is 15 mm×15 mm×40 mm and made with UPVC material (Fig. 4). Water outlets were connected to P2 piping using an elastic hose sealed with adhesive. Gas and water were separated in the fabricated pretreatment device. The gas entered the Hi Flow Sampler through the P1 piping that was filled with silicone to minimize moisture. The P3 was a water-draining switch.

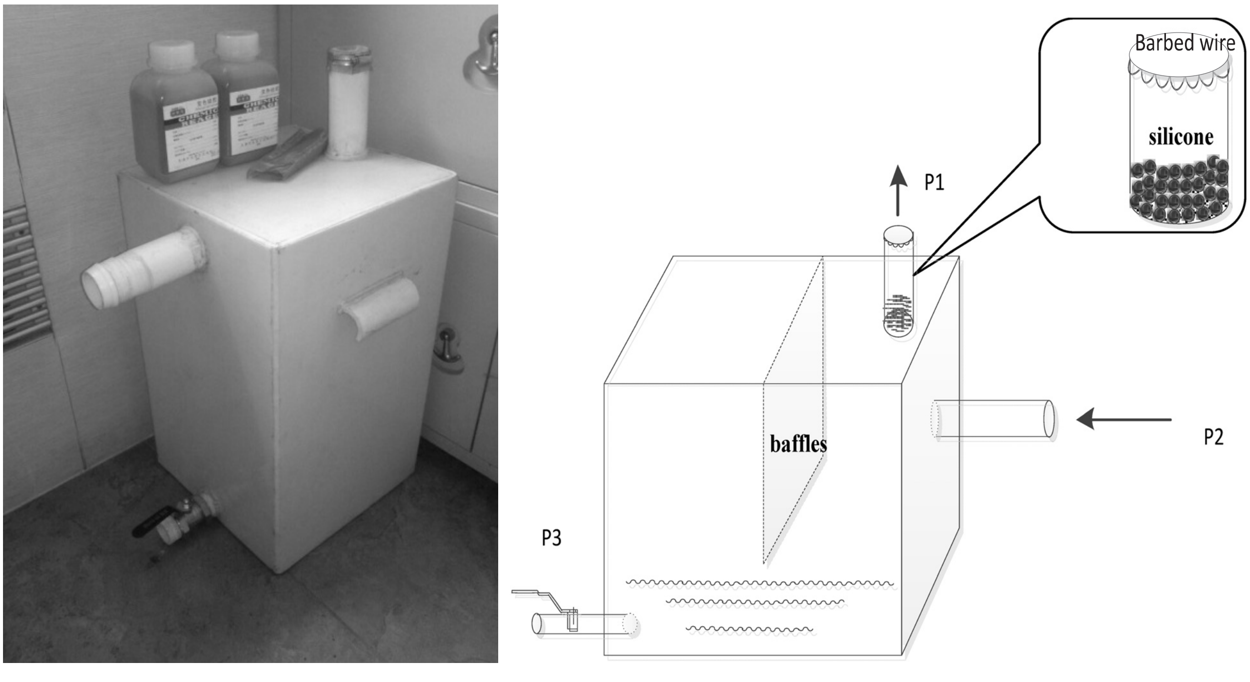

Fig. 4. Work flow of the self-made pretreatment.

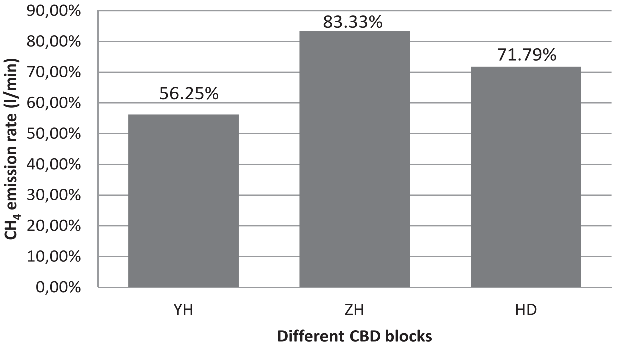

Fig. 5. CH_4 leak rates of the different blocks from the tubing.

Monitoring CH_4 Leakage from Other Components

There were two steps taken to monitor CH_4 leakage from other components. First, a remote methane leak detector detected the leak point. Second, the Hi Flow Sampler measured the leakage at the leak point.

Results and Discussion

CH_4 Leakage from Tubing

Fig. 5 summarizes the tubing leakage rate at the different blocks. The leakage rate of the ZH block was the highest, at 83.33%. The HD block was the next highest, at 71.79%. The YH block leakage rate was lowest, at 56.25%. The average leakage rate across all three blocks was 70.46%.

Fig. 6 shows the leakage volume of different blocks. The leakage from wells in the YH block ranged from 0.1 to 7.63 l/min; the average was 1.52 l/min. The leakage from wells in the ZH block ranged from 0.2 to 32.75 l/min; the average was 5.44 l/min. The leakage from wells in the HD block ranged from 0.2 to 44.3 l/min; the average was 6.72 l/min. The average across all 113 wells was 4.77 l/min.

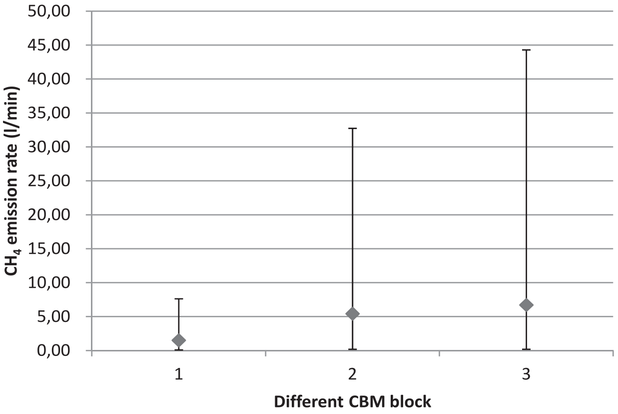

Fig. 6. CH_4 leak volume rates of the different blocks from the tubing.

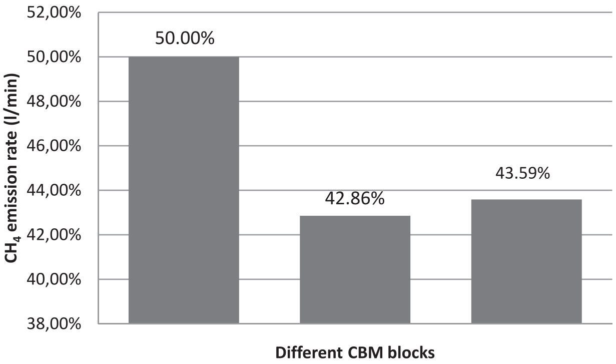

Fig. 7. CH_4 leak rates of the different blocks from the water outlet.

As discussed above, the leakage rate and the leakage volume of the YH block was the lowest; values were higher for ZH and HD blocks. There was considerable variation in average leakage across blocks, indicated by a large standard deviation in measurements. The high leakage in ZH and HD blocks was associated with particular geological conditions: rock strength is weak and easily collapses, leading to tilting and excessive tubing wear. Poor management practices aggravate the problem, resulting in problematic and damaged tubing not being replaced in a timely manner. Conversely, the geological conditions in the YH block are relatively stable, and regular and effective tubing management contributes to a low number of leakage points and a low leak rate. In summary, the leakage rate and the leakage volume of different wells were closely related to the management level.

CH_4 Leakage from the Water Outlets

Fig. 7 shows the water outlet leakage rate of different blocks. The leakage rate of the TH block was the highest, at more than 50%. The HD block was the next highest, at 43.59%. The ZH block was the lowest, at 42.86%.

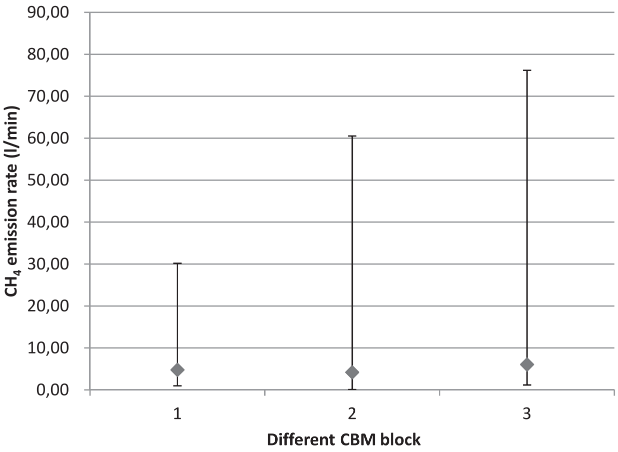

Fig. 8. CH_4 leak volume rates of the different blocks from the water outlet.

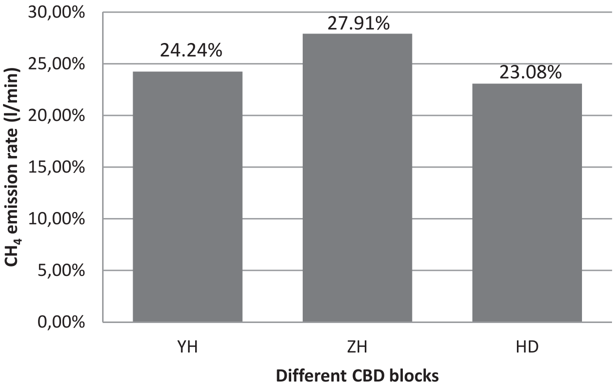

Fig. 9. CH_4 leak rates of the different blocks from the other components.

The average leakage rate is 45.48% for the water outlets, below the average for the tubing.

Fig. 8 shows the water outlet leakage volume of the different blocks. Leakage from wells in the YH block ranged from 1.00 to 30.20 l/min; the average was 4.80 l/min. Leakage from wells in the ZH block ranged from 0.10 to 60.55 l/min; the average was 4.22 l/min. Leakage from wells in the HD block was between 1.20 and 76.20 l/min; the average was 6.07 l/min. The average of the water outlet leakage rate across all wells was 5.02 l/min, slightly more than seen in the tubing. An unusually large leakage rate from a subset of the wells caused the higher average leakage from the water outlets.

The water outlet leakage rate and volume for each of the blocks showed little differences. The leakage rate in YH block wells was relatively high, as was the leakage volume in the ZH block. The main cause for the difference was that the CBM content in YH block was high; the gas dissolved into water at a super saturated state, which leaked into the oil tubing. Conversely, the HD and ZH blocks were larger and had relatively complex geological conditions, with large differences in CBM that led to leakage variation.

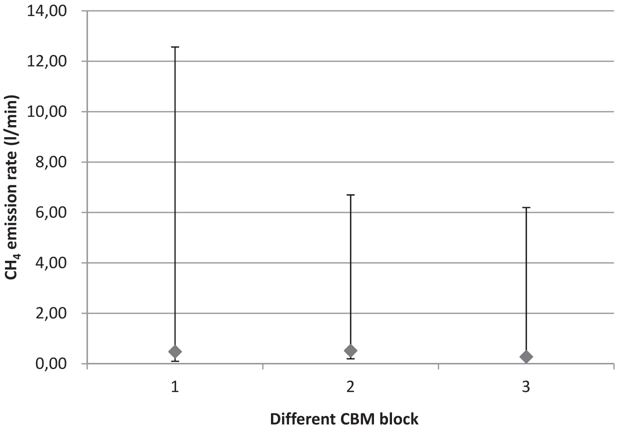

Fig. 10. CH_4 leak volume rates of the different blocks from the other components.

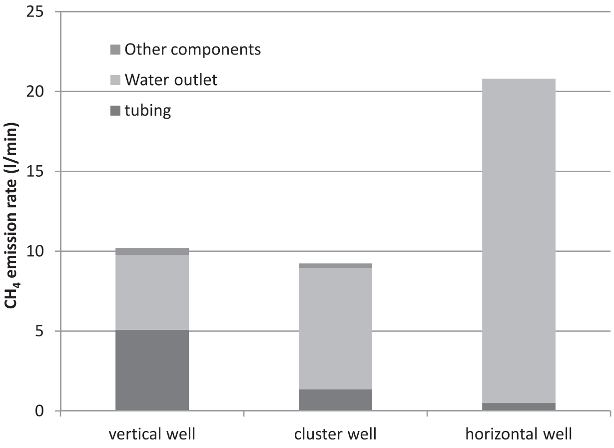

Fig. 11. CH_4 leak rates of the different processes.

CH_4 Leakage from Other Components

Fig. 9 shows the leakage through other well components across the different blocks. The leakage in ZH block wells was the highest, at 27.91%. The YH block was the next highest, at 24.24%. The HD block well had the lowest rate, at 23.08%. Fig. 10 shows the leakage volume through other components in the different blocks. The leakage volume in the YH block ranged from 0.10 to 12.57 l/min; the average was 0.48 l/min. The leakage volume in the ZH block well ranged from 0.20 to 6.70 l/min; the average was 0.52 l/min. The leakage volume in the HD block ranged from 0.20 to 6.20 l/min; the average was 0.28 l/min. The average across all wells was 0.43 l/min.

As discussed above, the leakage rate and volume through other well components were significantly below the tubing and the water outlets, and there was little variability across different blocks. Leakage of methane through other well components is mainly due to the sealing of the pressure meters and connection parts. Leakage was mainly associated with equipment servicing and overhaul schedules.

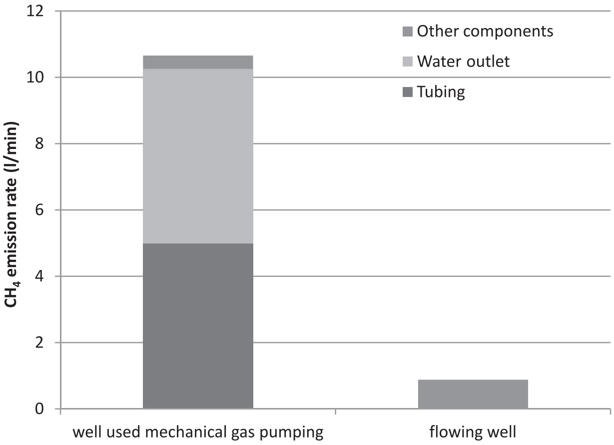

Fig. 12. CH_4 leak rates of the different running states.

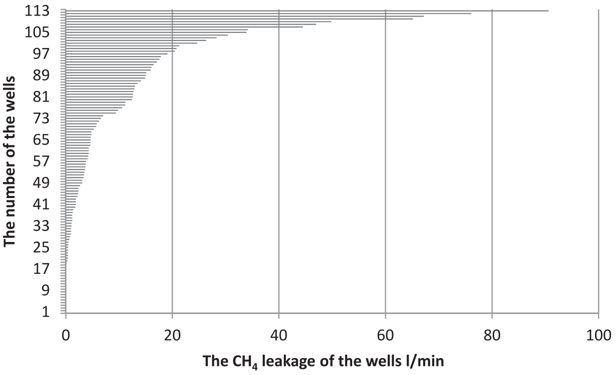

Fig. 13. CH_4 leak rates of all wells.

CH_4 Leakage of Different Processes

Of the 113 wells studied, 104 were vertical wells, eight were cluster wells, and one was a horizontal well. As Fig. 11 shows, leakage from the single horizontal well was the highest, with an average leakage of 20.80 l/min. Water outlet leakage accounted for 97.60% of the total leakage from this well. The average leakage volume of the 104 vertical wells was the next highest, with an average of 10.20 l/min. Here, the water outlets and tubing accounted for 95.66% of the total leakage. The leakage was the lowest in the cluster wells, with an average of 9.24 l/min. In these eight wells, 82.47% of the leakage was from the water outlets.

Leakage from the cluster and horizontal wells was mainly through water outlets, with relatively low leakage from tubing and other components. This low leakage may be because the cluster and the horizontal wells are newly constructed, thereby minimizing damage, wear, and poor management. The leakage from water outlets was likely high because of the cluster and horizontal wells' large contact areas between the coal bed and the pit-shaft. The coal bed drain discharge and the dissolved gas emission are larger, and the drain discharge of newly constructed wells during the first three years is at a relatively high level, leading to a correspondingly high volume of methane leakage.

CH_4 Leakage of the Different Running States

Of the 113 wells sampled, 108 are mechanical-gas pumping and five are natural-flowing wells. As Fig. 12 shows, the average leakage from mechanical gas pumping wells was 10.67 l/min, which includes leakage from tubing, water outlets, and other components. The average leakage from the natural flowing wells was 0.88 l/min, far below the mechanical-gas pumping wells.

CH_4 Leakage and Emission Factors of CBM Well

This study integrated the monitoring of tubing, water outlet, and other component leakage across 113 wells. Fig. 13 shows that leakages ranged from 0 to 90.60 l/min across all wells, with the average leakage 10.22 l/min. When considering all the wells: 17 wells (15.04% of all wells) had no CH_4 leakage, 58 wells (51.33% of all wells) had a single well leakage of less than 10 l/min, and 97 wells (85.84% of all monitored wells) had a single well leakage less than 20 l/min.

This study analyzed gas measurements from 113 wells, with an average gas production of 1,752 m^3/d. CH_4 emissions were released through tubing, water outlets, and other components. As Table 2 shows, tubing leakage was nearly equal to water outlet leakage, at 4.77 l/min and 5.02 l/min, respectively. Both were above the leakage of other components, at 0.43 l/min. In addition, the variability in tubing leakage (measured using standard deviation) was the highest, with leakage ranging from 0 to 44.30 l/min. Wells with good geological conditions and scientific management showed low leakage; wells with unfavorable geological conditions and improper management had much higher leakage. The variability in water outlet leakage was the next highest; variability across other components was the lowest.

Emission factors were calculated based on the average gas production and average leakage across wells. The emission factors of tubing, water outlets, and other components were 82.14, 86.45, and 86.45 kg CO_2-e t^{-1}, respectively. The total emission factor was 176 kg CO_2-e t^{-1} – far above the Australian emission level at 11.7 kg CO_2-e t^{-1}.

Conclusions

This study found that methane leakage from wells in the Qinshui Basin of Shanxi Province in northern China is mainly caused by leaks from water outlets and tubing. These two types of leakage account for 95.79% of total leakage, with a large standard deviation of 12.28. The

Table 2. CH4 emission factors of tubing, water outlet, and other components.

	Units	Tubing	Water outlet	Other components
Mean	l/min	4.77	5.02	0.43
Median	l/min	0	1	0
Std Deviation	-	12.28	8.05	1.53
Factor	Kg CO_2-e t^{-1}	82.33	86.65	7.42

primary differences in leakage between well groupings were due to geological conditions and management. Wells with unfavorable geological conditions and improper management had consistently higher leakage. The variability in leakage through water outlets was the next highest, followed by leakage through other components. Different processes and running states on CH_4 leakage have the greatest effects on leakage. Horizontal well leakage was highest in this study, with an average of 20.80 l/min. The average leakage of naturally flowing wells was 0.88 l/min, below that of wells stimulated through mechanical-gas pumping. The comprehensive emission factor across the 113 monitored wells was 176 kg CO_2-e t^{-1}, which is above the Australian emission level of 11.7 kg CO_2-e t^{-1}.

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References

1. YUN J., XU F.Y., LIU L., ZHONG N.N., WU X.B. New progress and future prospects of CBM exploration and development in China. Inter. J. Min. Sci. Tech. **22** (3), 363, **2012**.
2. HAMAWAND I., YUSAF T., HAMAWAND S.G. Coal seam gas and associated water: A review paper. Renew. Sust. Energ. Rev. **22**, 550, **2013**.
3. GOLDING S.D., RUDOLPH V., FLORES R.M. CO_2-enhanced coal bed methane. Int. J. Coal Geol. **82** (3-4), 133, **2010**.
4. FAN Y., MA J., ZhU L. Evaluating coal bed methane investment in China based on a real options model. Resour. Policy. **38** (1), 50, **2013**.
5. LIAO Y.Y., LUO D.D., LI W.L. Development strategy analysis of China's CBM. Acta Petrolei Sci. **33**, 1098, **2012**.
6. LUO D.K., DAI Y.J., XIA L.Y. Economic evaluation based policy analysis for coalbed methane industry in China. Energy. **36** (1), 360, **2011**.
7. DEMARTY M., BASTIEN J. GHG emissions from hydroelectric reservoirs in tropical and equatorial regions: Review of 20 years of CH_4 emission measurements. Energ Policy. **39** (7), 4197, **2011**.
8. DE RICHTER R., CAILLOL S. Fighting global warming: The potential of photocatalysis against CO_2, CH_4, N_2O, CFCs, tropospheric O_3, BC and other major contributors to climate change. J. Photoch. Photobio. C. **12** (1), 1, **2011**.
9. HEATH G., MELDRUM J., FISHER N., ARENT D., BAZILIAN M. Life cycle greenhouse gas emissions from Barnett Shale gas used to generate electricity. J. Unconv. Oil Gas Resour. **8**, 46, **2014**.
10. BRANTLEY S.L., YOXTHEIMER D., ARJMAND S., GRIEVE P., VIDIC R., POLLAK J., Llewellyn G.T., Abad J., Simon C. Water resource impacts during unconventional shale gas development: The Pennsylvania experience. Int. J. Coal Geol. **126**, 140, **2014**.
11. LAURENCE S., ADISA A. Life cycle environmental impacts of UK shale gas. Appl. Energy. **134**, 506, **2014**.