CH$_4$ generation simulation of drainage system in urban residential area

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Abstract. Based on the research of the dynamic simulation of CH$_4$ generation in the drainage system of residential area in Kunming, this paper initially explores the rules of CH$_4$ generation in domestic sewage. The experimental results show the hydraulic retention time (HRT) plays an important role in CH$_4$ generation. The shorter HRT is, the less CH$_4$ is generated, and the water flow leads to the reduction of CH$_4$. Pearson correlation analysis is conducted on the concentration of chemical oxygen demand (COD), total nitrogen (TN), sulphate, sulfide and that of CH$_4$ in wastewater. The result shows that the correlation between COD, COD/ sulfate and the CH$_4$ concentration of each sampling port is significant at the level of 0.01. Dissolved oxygen (DO) in the sewage of the simulation system is less than 0.2 mg·L$^{-1}$, that is, anaerobic condition is suitable for generating methane.

1. Introduction
Over the past century, large quantities of greenhouse gases have been emitted into the air owing to the human activities, which increases the risks of global warming. The impact brought about by global warming has been significant. For example, such greenhouse gases as methane and carbon dioxide have resulted in sea level rise and earth surface warming[1]. If no special policies or measures for cutting greenhouse gases are taken, the average temperature of the global surface shall hike up by 0.9~3.5 °C[2] by 2100. Methane is the second "contributor" to greenhouse gases only after carbon dioxide, existing about 12 years in the air[3]. Though its concentration in the air is less than carbon dioxide, the latter's impact on the global greenhouse effects is only 1/23~1/21 of the former's. As a matter of fact, 1kg methane equals to the quantity of carbon dioxide[4,5] from the generation of 20 kwh electricity, so the research and control on methane should not be overlooked.

At present, the research of CH$_4$ at home and abroad is ignored in urban drainage system, but the concern of CH$_4$ is mainly focused on its generation in refuse landfill, mud river reservoir and so on[6-10]. In the process of transporting wastewater in drainage system, the microbe may produce CH$_4$ gas by degrading organism on the anaerobic or anoxic condition [11-12] in sewage. In the sewer with bad ventilation, the long-time accumulated CH$_4$ will be a threat to human safety[2] when concentration of CH$_4$ mixed with air reaches 5%. Thus, it is of great practical significance to carry out the research on the pattern of CH$_4$ gas generation and emission in drainage system of domestic sewage for the study of China's urban greenhouse gas list.
Through the simulation of urban sewage drainage system (septic tank and inspection wells), this paper mainly focuses on the dynamic simulation test of residents’ domestic sewage so as to investigate the hydraulic factors' (HRT) influence on the pattern of CH$_4$ generation and studies the pattern and influential factors of CH$_4$ generation in sewer, which will provide important scientific evidences for the environmental management department in controlling the generation and emission of CH$_4$ gas in urban sewage drainage system.

2. Materials and methods

2.1. Experiment materials

Sewage and sludge required for the simulation test of residential sewage are collected from the septic tank in the residential community of Kunming University of Science and Technology.

2.2. Test apparatus

As is shown figure 1 below, the apparatus of the simulation test is mainly composed of four parts:

1) A polyethylene plastic barrel of the size 150 mm × 800 mm × 450 mm, the triple septic tank simulated at the volume ratio of 2: 1: 3 with the setting of gas sampling port 1# and 2 #;

2) Three plastic inspection wells with the length, width and height of 0.60 m, 0.52 m and 0.45 m, on which gas sampling ports 4 # and 6 # are settled

3) The PVC pipe simulation sewage drains between the septic tank and inspection wells, inspection wells and inspection wells, which the gas sampling port 3 #, 5 # are ;

4) The back-flow pipe by using a PVC pipe with a diameter of 20 mm. The maximum flow of circulating pump is 1.8 L • h$^{-1}$ and the head is 1.5 m. The dynamic simulation test is mainly used to study the influence of hydraulic factors on the pattern of CH$_4$ generation and discharge and that of anaerobic biodegradation under the natural conditions.

![Figure 1. Dynamic test device.](chart)
2.3. Test method

Sludge which is mixed with wastewater by the ratio of 5% in volume[13] is placed in the experimental device, which is an open effluent and the circulatory system. Within 24h, only gas collection is carried out. After 24h, the gas and water are collected simultaneously at a frequency of 1 time per hour. The monitoring lasts for three consecutive days, during which the sewage circulation within the device on the first and the second day makes the sewage flow and the sewage is static on the third day after stopping the circle. The concentration changes of COD, TN, sulfate, sulfide, dissolved oxygen (DO) and gas in sewage are observed under natural conditions.

The gas is monitored by the iBrid MX6 complex gas detector. The COD, TN, sulfate and sulfide are measured by referring to the methods in Water and Wastewater Analysis[14]. Dissolved oxygen (DO) is determined by using Type 706 multi-parameter detector.

3. Results and discussion

3.1. Changes of CH₄ concentration in different periods

3.1.1. Changes of CH₄ concentration from 24h to 34h. Anaerobic biodegradation of domestic wastewater takes place on the condition of ambient temperature. CH₄ concentration in monitoring ports is tested every one hour after 24 hours. The change of CH₄ concentration in monitoring ports 1 - 6# from 24h to 34h is presented in Figure 2.

As can be seen from Figure 2, at 5# and 6# sampling ports CH₄ is first detected at the 28th hour; the CH₄ concentration begins to decrease at the 34th hour and its concentration range is 0-825.9569 mg·m⁻³ and 0-884.9539 mg·m⁻³. At sampling ports 3 # and 4 # CH₄ is first detected at the 29th hour; the concentration begins to decrease at the 31st hour and its concentration range is 0-08.4534 mg·m⁻³ and 0-767.4911 mg·m⁻³. At sampling ports 1 # and 2 # CH₄ is detected first at the 30th hour; the CH₄ concentration begins to decrease at the 31th hour and its concentration range is 0-649.4156 mg·m⁻³ and 0-708.4534 mg·m⁻³. Chen Wei[15] et al. points out that the rate of sewage flow affects the accumulation and transportation of solid sediments in sewage. Since the sewage in the device is in circulation in the first 48 hours, part of the sludge in the simulated septic tank will be carried to the rear check-in and drain pipes with continuously flushing the sewage, which results in the increase of sludge in the inspection well or the septic tank in the flow direction. Methanogens may exist in the gas phase in the sludge, therefore the first detection of CH₄ generation is at 5 # and 6 # sampling ports which is away from septic tank, while the last detection of CH₄ generation is at 1 and 2 # sampling ports on the septic tank. In the later half period, the CH₄ concentration decreases because the gas generation has decreased due to the turbulence of the Sewage which makes the microorganism in the sludge unable to stay in a relatively stable environment. Albert Guisasola[4,16] et al. puts forward the idea that the formation of CH₄ in sewer pipelines is positively correlated to hydraulic retention time (HRT) and A/V (area to volume ratio). The longer the HRT and A/V are, the more CH₄ is generated, and the short HRT is unfavorable to the growth of microorganisms.

Table 1. Correlation analysis on the concentration changes of HRT and CH₄ formula:  
\[
y = \frac{A}{1 + \exp((x-C)/D)}.
\]

| Sample outlet | A    | B    | C    | D    | R²   |
|---------------|------|------|------|------|------|
| 1#            | 625.45 | 627.17 | 29.09 | 0.0062 | 0.994 |
| 2#            | 672.66 | 675.25 | 29.21 | 0.02  | 0.995 |
| 3#            | 684.46 | 683.03 | 28.88 | 0.04  | 0.995 |
| 4#            | 708.07 | 708.07 | 28.90 | 0.04  | 0.985 |
| 5#            | 767.23 | 768.99 | 27.80 | 0.17  | 0.986 |
| 6#            | 816.29 | 817.38 | 27.79 | 0.15  | 0.991 |
In accordance with Pearson correlation analysis on the concentration changes of HRT and CH₄, the result indicates that the concentration changes of CH₄ at each sampling port are significantly correlated to HRT at the level of 0.01, i.e., which has a significant effect on the generation of CH₄ and also the concentration changes of CH₄ at each sampling port can well fit for the Boltzmann gas dynamics equation. The results of the fitting are shown in Table 1:

3.1.2. Changes of CH₄ concentration from 48h to 58h. The change of CH₄ concentration in monitoring points 1 - 6# from 48h to 58h is presented in Figure 3.

![Figure 2](image1.png)  ![Figure 3](image2.png)

**Figure 2.** The changes of CH₄ concentration between 24 to 34 hours.  
**Figure 3.** The changes of CH₄ concentration between 48 to 58 hours.

It can be seen from Figure 3 that the first sampling ports to monitor the generation of CH₄ are 5 # and 6 #; At the 51st hour, the sampling ports of 5 # and 6 # begin monitoring the generation of CH₄, and the variation range of the concentration is 0-826.2428 mg·m⁻³. At the 54th hour, the CH₄ concentration reaches the top and then presents a downward trend. At the 52nd hour, the sampling ports of 3 # and 4 # begin monitoring the generation of CH₄, and the respective variation range of the concentration is 0-708.2081 mg·m⁻³, and 0-767.2255 mg·m⁻³. At the 53rd hour, the sampling ports of 1 # and 2 # begin monitoring the generation of CH₄ and the variation range of the concentration is 0-708.2081 mg·m⁻³. In the experiment, the sewage circulation device has been running for 48 hours, and after that the environment of the whole system tends to be stable and HRT becomes longer. Since the sewage inside the device keeps flowing in the first 48 hours and brings some sludge from the septic tank, the sampling ports of 5 # and 6 # which are far away from the septic-tank are made to first monitor generation of CH₄. Then after the 54th hour, the CH₄ concentration begins to decrease because after three-day operation of the sewage in the device, the microorganisms continue to decompose the limited organic matter in the sewage, and finally stop the gas generation.

In accordance with Pearson correlation analysis on the concentration changes of HRT and CH₄, the result indicates that except the sampling ports of 1 # and 2 #, the concentration change of CH₄ at other sampling ports has significant correlation with HRT at the level of 0.01, i.e., and HRT has greater impact on generation of CH₄. Ports 1 # and 2 # can better fit for the Gauss model equation relatively; other results are fit for the Boltzmann gas dynamics equations. The fitting result is shown in Table 2 and Table 3:
Table 2. Gaussian model fitting Effects of HRT on CH4 formula: \(y=A+B\times\exp(-2\times((x-C)/D)^2)\).

| Sample outlet | A     | B     | C     | D     | R2   |
|---------------|-------|-------|-------|-------|------|
| 1#            | -46.39| 1097.81| 55.02 | 3.65  | 0.812|
| 2#            | -47.64| 1058.03| 55.02 | 3.73  | 0.787|

Table 3. Boltzmann gas dynamic equation fitting Effects of HRT on CH4 formula: \(y=A-B/(1+\exp((x-C)/D))\).

| Sample outlet | A     | B     | C     | D     | R2   |
|---------------|-------|-------|-------|-------|------|
| 3#            | 668.72| 668.90| 51.78 | 0.11  | 0.985|
| 4#            | 682.69| 659.56| 51.72 | 0.0078| 0.967|
| 5#            | 758.62| 759.34| 50.77 | 0.13  | 0.965|
| 6#            | 741.76| 742.10| 50.77 | 0.12  | 0.968|

3.2. Correlation analysis of water quality change and Pearson.

Within 58 hours, the concentration changes of COD, total nitrogen, sulfate and sulfide are shown in Figure 4.

From Figure 4, it is known that the concentration of COD within 58 hours decreases from 147 mg L\(^{-1}\) to 18 mg L\(^{-1}\), and degradation rate reaches 87.76%; the concentration of TN decreases from 15.28 mg L\(^{-1}\) to 2.26 mg L\(^{-1}\) and the degradation rate reaches 85.21%, which both shows a decreasing trend. The concentration of COD fluctuates because after the microorganisms die in the sewage, the substances in the cells are released so that the COD increases. The microorganisms may produce CH\(_4\) by utilizing organics and other substances to reduce COD. The microorganisms in the device meet the needs of its own metabolism by utilizing organics; CH\(_4\), as one of the products of metabolism, presents the pattern of gas generation in consistency with the anaerobic biodegradation of methanogens.

Pearson correlation analysis is conducted on each water quality index and the CH\(_4\) concentration at each sampling port, and the results are indicated in Table 4.

Table 4. Correlation analysis of methane and COD,TN,COD/sulphate,sulfide.

| Sampling port | COD correlation | TN correlation | COD/ Sulfate correlation | Sulfide correlation |
|---------------|-----------------|----------------|--------------------------|--------------------|
| 1 #           |                  |                |                          |                    |
| Pearson correlation | -.772  | -.544          | -.782                    | .648               |
| Significance (bilateral) | .005   | .083           | .004                     | .031               |
| Pearson correlation | -.772  | -.540          | -.781                    | .645               |
| 2 #           |                  |                |                          |                    |
| Pearson correlation | -.949  | -.749          | -.957                    | .641               |
| Significance (bilateral) | .000   | .008           | .000                     | .034               |
| 3 #           |                  |                |                          |                    |
| Pearson correlation | -.943  | -.746          | -.952                    | .627               |
| 4 #           |                  |                |                          |                    |
| Pearson correlation | -.929  | -.852          | -.926                    | .602               |
| 5 #           |                  |                |                          |                    |
| Pearson correlation | -.929  | -.849          | -.924                    | .596               |
| 6 #           |                  |                |                          |                    |
| Pearson correlation | -.927  | -.849          | -.924                    | .596               |
As is shown in the table above, the correlation of COD, COD/sulfate and the CH₄ concentration at each sampling port is significant at the level of 0.01. TN has no correlation with the CH₄ concentration at the sampling ports of 1 # and 2 #, and has significant correlation with the CH₄ concentration at the sampling ports of 3 #, 4 # and 5#. The correlation between sulfide and the CH₄ concentration at the sampling ports of 1 #, 2 #, 3 # and 4 # is significantly related at the level of 0.05, and has no correlation with the CH₄ concentration at the sampling ports of 5 # and 6 #.

3.3. Concentration changes of O₂ and CO₂ in different periods

O₂ directly affects the concentration of dissolved oxygen (DO) in sewage, and DO is a decisive factor in the anaerobic, facultative, or anoxic environment of sewage. The concentration changes of O₂ in the air in different periods are shown in Table 5.

### Table 5. The changes of O₂ concentration.

|     | 24~34h       | 48~58h       |
|-----|--------------|--------------|
| 1#  | 198.783~205.195 | 193.439~199.852 |
| 2#  | 204.127~209.470  | 203.058~207.333  |
| 3#  | 204.127~207.333  | 204.127~207.333  |
| 4#  | 205.195~210.539  | 209.470~201.989  |
| 5#  | 204.127~207.333  | 203.058~207.333  |
| 6#  | 204.127~206.264  | 203.058~207.333  |

It can be seen in Table 5 that O₂ content in the analogous device is much lower than that in the outside air (221.226 g/m³). The oxygen concentration in the air affects the dissolved oxygen concentration in the sewage due to air diffusion. The concentration changes of dissolved oxygen in the system from the 24th to 58h are presented in Figure 5.

![Figure 4](image4.png)  ![Figure 5](image5.png)

**Figure 4.** The changes of COD and TN concentration.  
**Figure 5.** The changes of DO concentration between 24 to 58 hours.
It can be seen from Figure 5 that the decreasing trend of DO concentration is obvious in the first 26 hours, and then tends to be stable. This is ascribed to the fact that microorganisms metabolize organic matters consumes DO in sewage, thus DO in sewage is reduced; DO fluctuates may be ascribed to the continuous circulating of the device, which leads to a small change of DO. The DO concentration varies from 0.01 to 0.04 mg L⁻¹, which creates an anaerobic environment (DO<0.2 mg L⁻¹) that is suitable for MB's growth, i.e., the simulated system has the basic conditions for the generation of CH₄.

4. Conclusions
1) The flow velocity of sewage has certain influence on the generation of CH₄. The flow velocity of sewage affects HRT; the larger the flow rate is, the shorter the HRT is. The generation of the CH₄ is restrained. In accordance with the Pearson correlation analysis on the concentration changes of HRT and CH₄, from 24h to 34h, its significance is significantly correlated at the level of 0.01; within 48-58h, except for the sampling ports of 1# and 2#, the concentration change of CH₄ at other sampling ports is significantly correlated to HRT at the level of 0.01, which indicates that HRT plays a key role in the generation of CH₄. The water flow not only takes away sediment in the sewage, but also causes the migration of CH₄.

2) The urban sewage drainage system mainly exists in the anaerobic environment. With the progressive reaction, both concentrations of COD and TN in the sewage decrease. Anaerobic biodegradation is performed in microorganisms by decomposing organic matters in sewage to produce CH₄, CO₂ and other metabolites. The results of Pearson correlation analysis on each water quality index and the CH₄ concentration of each sampling port indicate that the correlation of COD, COD/ sulphate and the CH₄ concentration of each sampling port is significant at the level of 0.01.

3) The O₂ concentration in the simulated urban sewage drainage system is significantly lower than that in the atmosphere, and the O₂ concentration affects the DO in the sewage due to air diffusion, which affects the generation of CH₄. The DO in the simulated sewage is less than 0.2 mg L⁻¹ in the anaerobic condition, which is suitable for the generation of CH₄.

4) The following should be noted in designing urban domestic sewage discharge pipe network: the pipe network should reduce HRT and improve DO; the drainage pipe should be arranged with an inclined angle and dredged regularly to avoid sewage being left in the drain for a long time; increase pipe vent settings but reduce microbial anaerobic fermentation, which may produce excessive CH₄; set up a complete pipeline network sewage and CH₄ production monitoring system; build temporary collection wells and temporarily store sewage during the peak hours of water use, but to empty it in the low water period; detect CH₄ production in different regions; set the valve to change the sewage flow direction to reduce the pipe exhaust pressure.

References
[1] ZHANG Fu-Kai, XU Long-Jun 2004 Effects of Methane on Global Warming and Measures to Reduce CO₂ Emissions [J] Mining Safety and Environmental Protection 31 (5) 6-9
[2] EI-FADEL M, MASSOUD M 2001 Methane emissions from wastewater management.[J] Environmental Pollution 114(2) 177
[3] EGGLESTON H S, BUENDIA L, MIWA K, et al. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme.IGES Japan
[4] GUJASOLA A, DE H D, KELLER J, et al. 2008 Methane formation in sewer systems [J] Water Research 42(6-7) 1421
[5] Li Gui bai, Yang Yan ling 2007 The third generation of urban drinking water purification process - the core technology of ultrafiltration combination of technology [J] Water Supply and Drainage 33 (4) 1
[6] Yu Hong xian, Ci Xue lun, Huang Puli 2012 Daily variation of methane flux over the water-air interface in summer in Nihe Reservoir [J] Journal of Harbin University of Commerce
(Natural Science Edition) 28 (1) 36-39

[7] Fei Ping'an, Wang Qi 2008 Methane oxidation mechanism of landfill cover and its influencing factors [J] Renewable Energy 26(1) 97-101

[8] LIEBNER S, ZEYER J 2012 Methane emissions from an alpine fen in central Switzerland [J] Biogeochemistry 109(1-3) 287-299

[9] BARLAZ M A, GREEN R B, CHANTON J P, et al. 2004 Evaluation of a biologically active cover for mitigation of landfill gas emissions [J] Environmental Science & Technology 38(18) 4891-9

[10] Yang Jun, Huang Tao, Zhang Xi hua 2007 Study on Quantitative Model of Methane Production in Organic Landfill [J] Journal of Environmental Science 20(5) 79-83

[11] Wang Kai jun, Jia Li min 2002 Urban sewage biological treatment of new technology development and application [M] Chemical Industry Press

[12] Chen Zhen min 2004 A preliminary discussion on the methods to improve methane production by anaerobic treatment [J] Journal of Environmental Engineering 5(5) 43-47

[13] BACHMANN R T, SAUL A J, EDYVEAN R G 2007 Investigating and modelling the development of septic sewage in filled sewers under static conditions: a lab-scale feasibility study [J] Science of the Total Environment 388(1–3) 194-205

[14] Zhou Yu, Huang Jian hong, Ning Ping, et al 2013 Simulation experiment of methanogenic law of wastewater discharge system in Kunming [J] Journal of Environmental Engineering 7(9) 3531-3536

[15] Chen Wei, Song Pei di, Zheng Xing can et al 2006 Influencing factors of hydrogen sulfide poisoning in sewage system and control measures [J] Water Supply and Drainage 1 15-19.

[16] GUISASOLA A, SHARMA K R, KELLER J, et al. 2009 Development of a model for assessing methane formation in rising main sewers [J] Water Research 43(11) 2874