

Family-size Biogas Plant Using Manure and Urine Mixture at Ambient Temperature in Semi-arid Regions of Northwestern China

Wenguang Ding, Yang Wu, Xia Wang, Yayu Gao

Abstract—Biogas, a clean renewable energy, is attracting a growing concern of researchers and professionals in many fields. Based on the natural and climatic conditions in semi-arid regions of northwestern China, the present study introduces a specifically-designed family-size biogas plant (with a digester of $10m^3$) with manure and urine of animals and humanity as raw materials. The biogas plant is applicable to areas with altitudes of more than 2000 meters in northwestern China. In addition to the installation cost, a little operational expenditure, structure, characteristics, benefits of this small-scale biogas plant, this article introduces a wide range of specific popularization methods such as training, financial support, guided tour to the biogas plant, community-based group study and delivery of operational manuals. The feasibility of the biogas plant is explored on the basis of the availability of the raw materials. Simple operations contained in the current work increase the possibility of the wide use of this small-scale biogas plant in similar regions of the world.

Keywords—biogas, family-size biogas plant, northwestern China, popularization

I. INTRODUCTION

AN increasing interest in clean renewable energy has been shown due to scarcity of oil, rising price of fossil fuels, energy security and responsibility of reducing green house gas emission. Solar, wind, nuclear and other new energies are widely used all over the world. Although they can not replace traditional fossil fuels, they still represent a trend towards energy consumption. Biogas, a clean environment-friendly biomass fuel consisting mainly of methane (CH_4), has been used in China for thousands of years. Marco Polo mentions the use of covered sewage tanks. It probably goes back 2,000-3,000 years ago in ancient Chinese literature[1]. The technology has already been extended to India, Pakistan, Canada and many other countries. However, accumulated experience and previous studies suggest that ambient temperature and cost efficiency have to be taken into account in the construction of

biogas plants with an underground digester where anaerobic fermentation of the organic materials takes place. Both seem to play a negative role in the popularization of biogas plants in China because the climate in China varies considerably from south to north. The dramatically changing temperature restricts considerably the development of biogas plants which depend to a great extent on the activities of microorganisms for which low temperature is not favorable. Therefore, only places with a high ambient temperature are suitable for biogas plants in China whereas countries with widely-built biogas plants, including India and Pakistan, are all located in areas with a high ambient temperature. As a result, according to Jingyi Han, some biogas plants constructed in northern China are not successful [2].

Compared to other northern parts of the same latitude, northwestern China has an even worse climate, but it has never been mentioned in previous publications. Drought as well as low temperature contrast sets enormous obstacles to the operation of traditional biogas plants although they proved to be successful in southern China according to empirical evidence. After years of experiments and innovations, a new system was designed and operated in Jingyuan County and proved to be adaptive to local conditions in Gansu, one of typical semi-arid regions of northwestern China.

Located in the north latitude between $30^{\circ}10'$ and $37^{\circ}15'$, east longitude $104^{\circ}18'$ and $104^{\circ}18'$, the altitude of Jingyuan county ranges from 1279 to 3017 meters and the average temperature is $8.8^{\circ}C$. Its annual precipitation is 240 mm. Farmers live in poor economic conditions with an average income of RMB 1,000 per capita per year.

This article will provide a detailed description of the new biogas plant which might be suitable for other regions with similar climate conditions. The economic and other benefits will be analyzed further with the application of the biogas plant.

II. MATERIALS AND METHODS

The Jingyuan biogas plant, with a digester, livestock sheds, a toilet, a green house and a kitchen, can work effectively in winter when the ambient temperature is as low as $-15^{\circ}C$ and save labor from collecting firewood in the traditional way. And the greenhouse within this biogas system can provide a warmer environment to increase the growth of the livestock and keep the digester at a relatively higher temperature. Such pilot plants, proving to be effective, have been mentioned in Qi's

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research [3]. Chen has systematically summarized the different combination methods of biogas plants all through China[4]. However, the Jingyuan system has made several innovations. The rural fuel consumption pattern changes dramatically with the use of biogas. The result is a clean and healthy kitchen, which has a positive effect on the health of women in a long term.

A. The Combination Structure Of The Biogas Plant

The whole system is made up of a biogas plant, a digester, livestock sheds, a toilet, a green house and a kitchen. The system is also called "five-in-one". The digester is built underground with its upper part serving as a gas holder. The livestock sheds and the toilet with inlet pipes into the digester are built on the ground, covering the underground digester. The green house includes the livestock sheds, the toilet and the passage which in winter are all covered with plastic films. The whole unit is very popular in the northern China[5]. The livestock sheds can, on one hand, keep the biogas plant underground warm, and on the other hand, animal dung and urine can flow into the biogas plant via a PVC pipe without transportation though the design of a slight bevel ground.

Table 2 indicates that the improved design of the traditional biogas plant would be more effective than traditional biogas plants. Generally, a traditional biogas plant could only be normally operated at 8°C or above.

However, the improved one could supply biogas at even -15°C. A small, but smart improvement could bring about a big change.

Building the big hydraulic tank of the traditional Chinese biogas plant is time consuming and the construction cost is high, and the materials in the digester flow easily into the hydraulic tank which is designed to provide pressure for methane with the help of water's gravity inside, causing a waste of the manure and urine. The outlet passage at the bottom of the digester affects the fermentation process and reduces the capacity of biogas. The materials easily form clots resulting from lacking of agitation and slurry outlet is inconvenient so that the farmers have to perform an intensified outlet every year.

However, the Jingyuan biogas plant boasts four major innovations.

1) A circumfluence pipe is added between the extraction tank and the digester in order for the slurry to be mixed in the tank and flow back into the digester. So the agitation is generated in the digester and the nutrient elements and microorganism are redistributed back to the digester.

2) A manual slurry extractor is designed to make the slurry move up and down easily in the digester, which helps promote the cycling process and increase the multiplying of the bacteria. The slurry can also be extracted into the tank for better blending and this mechanism can keep the digester work without frequent and intensified outlet operation.

3) The bottom line of the 1.2-meter-deep hydraulic tank is higher than the bottom of the digester, which can prevent the materials from flowing out before complete fermentation while at the same time it adequately provides pressure for biogas.

4) The slope hydraulic passage of the Jingyuan biogas plant with a diameter of 30 cm also leads to a reduction of material outflow.

The Jingyuan model is designed on the basis of local natural environment that is characterized by drought and low ambient temperature in winter. It is practical, feasible, easy to operate, and energy-saving.

B. The Functions Of The Greenhouse

The low temperature in northwestern China in winter constrains the activities of microorganisms in the biogas plant, which can explicitly explain why biogas plants are not popular there. However, thanks to multiple functions and designs, biogas plants work well in other countries at similar or even lower temperature, which offers an abundance of references. Smaller family-size biogas plants 10 m³ will be a priority in northern China, especially in rural areas, for the majority of production activities are based on families in remote hilly regions. In a family-size biogas plant, the greenhouse (including the livestock sheds, the toilet and the passage) can solve the heating problem perfectly. The reasons are as follows.

1) The volume of a family-size biogas plant is about 10 m³, the size that farmers can afford and the size that is easy to be popularized.

2) The livestock sheds, the toilet and the passage with a plastic film cover, create warm conditions for the livestock in winter and accelerate animal growth as less energy is consumed to protect against the cold weather which has also been proved in Dang's research[6].

C. The Benefits Of The Warm Livestock Sheds

The temperature in the livestock sheds with the plastic film cover is much higher than the ambient temperature in winter. For instance, the temperature in the livestock shed covered with plastic films would reach 8°C or higher, whereas the ambient temperature was -10°C, even -15°C. As a result, the livestock inside grow faster than those fed outside in winter. Farmers can save forage, and the shortened feeding cycle would allow farmers to feed more livestock within a year. In this way, the farmers' expenditure is reduced and the income is increased. As the livestock sheds is built upon the biogas digester, the animal urine and dung do not need to be transported for a long distance in the traditional way, which in turn saves labor and decreases labor intensity. Our interviews with farmers indicate that farmers who have a biogas plant can send a laborer out of their communities to do migrant or seasonal work, which could help earn about RMB 18,000 to RMB 20,000 a year. Therefore, a biogas plant could also indirectly generate income for those poor farm households.

D. The Toilet

The toilet built upon the digester is cleaner than the traditional one, for the human excreta can be flushed into the digester directly through the inlet pipe. In addition, the improved toilet has fewer flies, less smelly and warmer in winter than the traditional one. Environment suitable for the generation of

mosquito and flies has been revised so the sanitation condition has been greatly improved. The risk of spreading contagious diseases by mosquitoes and flies is greatly reduced.

E. The Kitchen

A village woman had to spend more than two hours preparing meals before the biogas plant was introduced: one hour for collecting fuel wood and the other for cooking. The kitchen smoke seriously damaged people's health and the woman who takes the responsibility of cooking suffered the most. The introduction of the biogas plant can save her two hours a day and the cooking conditions have been improved. The H_2S which is an element of biogas is absorbed in the system, so the gas used for cooking is flavorless. As the biogas substitutes firewood as fuel inside the room, and as the biogas is specially designed for rural families instead of commercial organizations, the complicated components of the biogas plant are not necessary as mentioned in Kapdi's research [7]. The rural biogas plant does not require expensive equipments, and the price for installing such a plant is relatively lower. In some areas of China, the development of economics has witnessed the shifting pattern of energy consumption from biomass to cleaner commercial sources like LPG, electricity and natural gas [8]. In Gansu province, however, the laggard development of economics hampered this process. It is still years away for the rural people to use commercial fuels. Even in a few years such trend is obviously observed in Gansu province, the low income of rural people could be a fatal obstacle to the shifting of the fuel pattern. However, with greater efforts in reduction of CO_2 emission, the Chinese government would support less developed regions like Gansu province to demonstrate intensified commercial biogas production by using both animal manure and crop.

III. RESULTS AND DISCUSSION

Due to the low availability of fossil energy, biomass is the sole source of energy of rural villagers in the disadvantaged areas. Formal studies show that biomass consumption in some rural poverty regions accounts for 56% of their total energy consumption, of which new energy such as biogas and solar energy only constitute 3% [9]. The annual gas production capacity of a Jingyuan biogas plant of $10 m^3$ can amount to $500 m^3$, which is 25% more than the capacity of the traditional one in the same latitude.

A. Benefits Of Jingyuan Biogas Plant

1) *Economic Benefits Of Jingyuan Biogas Plant:* An survey carried out in 100 farm households using biogas plants in Jingyuan county indicates that a $10 m^3$ biogas plant can save a rural family RMB 600 from buying fertilizers, RMB 300 to 400 from buying pesticides and RMB 460 for energy cost for a six-members family, the average family size there. Totally, a family using the biogas could save as much as RMB 1360 to RMB 1460 per year, whose economic value is equivalent to cost of about 4-5 tons of coal, or more than an average net income per capita per year in poverty regions in China.

The family could use the saved money to support a junior middle school student to seek basic education for one year. In addition, as mentioned above, the indirect income of a biogas plant is about RMB 18,000 to RMB 20,000 a year.

2) *Benefits For The Environment, Health, And Education:*

The dung and urine of livestock are collected as raw materials in the biogas plant, so the sanitary condition has been improved and the medium for spreading pathogenic bacteria is eliminated. It indicates that the improvement of the local sanitation can not be measured through economic methods even though the phenomena is obviously noticed [10]. The smoke-free kitchen is good for women's health and improves their living standard. In addition, without the traditional way of cutting trees or bushes, 667 biogas-supported families will save 1 hectare forest within one year.

3) *Utilization Of Residual Dreg And Fermented Liquor:*

The utilization of residual dreg and fermented liquor has been mentioned in other articles for many times. According to Xinshan Qi, the residual dreg is usually used as fertilizer for the soil [3]. In this article, it concludes that the residual dreg can be added to the soil in all the stages of plant growth, which is also confirmed in the present study. Moreover, the research shows that fermented liquor can be used as pig feed, pesticides and catalyst to improve the survival rate of seed germination [7]. Four steps are required in the process of improving the germination ratio of seeds with fermented liquor.

1) Select qualified seeds and expose them to the sunshine for one or two days.

2) Pack seeds with sack and leave one quarter space for each sack.

3) Clear up slurry outlet tank and leave enough space for soaking seeds.

4) Immerse the rope-tied seed packs in the fermented liquor and fix the rope to the edge of the tank. The soaking time should be within 12 hours and depend on the seed varieties.

5) Wash the seeds with clean water and leave them in the sun to dry.

The investigation shows that the fermented liquor can help improve the ratio of germination and reduce the risk of seeds being eaten by rats. According to observation, different species would have different germination rates. And more detailed scientific data would be obtained at further study in this paper.

B. Daily Use Of The Biogas Plant And Daily Management Methods

In rural areas, most of the farmers are poorly-educated. If the methods of operating the biogas plant are too complex, it will be impossible for the farmers to master. So the key lies at the easy approaches of management and the reliable performance of the biogas plants. The greenhouse built on the ground of the biogas plant can guarantee that the temperature is more than $10^\circ C$ which allows the biogas plant to function in all seasons.

1) *The Method For Controlling pH:* In the process of fermentation, the microorganisms prefer an environment in neutral or slight alkaline which can be achieved after a natural fermentation process. Then the pH indicator will fluctuate

around the middle pH of the environment. The extent of fluctuation depends on the ambient temperature, concentration of the accumulated slurry, fermented liquor and frequency of adding raw materials and extracting slurry. When the temperature varies between 24°C and 27°C, 6 days is long enough for the digester to reach neutral pH in a newly-built biogas plant according to field study. When the temperature drops to 18 °C and 20°C in autumn, it will take 14 to 18 days to reach a stable pH. In practice, farmers rarely need to adjust pH. However, high concentration of fermented liquid and improper management may lead to the dysfunction, and adding alkaline materials to the digester is necessary.

The research shows pH in biogas plant is more likely to decline to acid than alkaline especially at the very beginning of a new biogas plant. Inputting too many raw materials and inadequate inoculation can lead the pH to drop to 5.5, which has an enormous negative impact on the activity of microorganisms. Local professionals from farmers who are well-trained or have much experience can help the new users to solve this problem. Their solutions fall into four aspects:

- 1) Adding more inoculation microorganisms.
- 2) Adding limewater and agitating the raw materials to adjust pH.
- 3) Adding plant ash to the biogas plant and agitating the mixture.
- 4) Discharging parts of the raw materials and adding fresh organism raw materials rich in nitrogen and water to lower the ratio of C:N.

The present study demonstrates that the organic materials in the new biogas plant will be consumed and the pH tends to increase one month later. Adding some fresh cattle dung, horse manure or some fresh grass can solve the potential problem. The percentage of Liquid contained in the raw materials should be between 90% and 94%.

2) *The Amount Of Daily Input Raw Materials And The Ratio Of Different Raw Materials:* 2 m³, to 3 m³, of raw materials should be added into a newly set up 10 m³, biogas plant. It usually takes about 20 days to produce gas after it is set up. The intervals for inputting into and discharging raw materials from the biogas plant should range from 7 to 10 days. Previous studies show that the adaptive time for microorganisms is over 90 days, depending on the design and raw materials [11]. The amount of dung for each addition should be around 20 kilograms, accounting for 3% to 5% of the total in the tank. The digestion speed should also be taken into consideration with each addition. And the ratio of C:N is an essential factor for fermentation process. The ideal ratio of C: N is 25:1 to 30:1.

Table 3 shows that cow dung and horse dung are ideal animal manure for fermentation because their C:N is just close to the ideal ratio as mentioned in Table 3. In reality, two to three pigs or one cattle could provide enough dung materials to a 10 m³, biogas plant after it is used.

C. The Popularization Of Biogas Plants

It takes time to extend quality biogas plants in rural regions of China to replace the traditional ones since it is a systematic

process of technique training, financial support, demonstration and maintenance [12]. All the problems are addressed as follows.

1) *Technique Training:* The training for building and using the biogas plants contains six parts:

- 1) Construction techniques of the biogas plant.
- 2) Raw materials and conditions for the proper operation of the biogas plant.
- 3) Daily management and safety instructions.
- 4) Frequently-met malfunctions and maintenance.
- 5) Introduction to the ancillary apparatus in kitchen and skills for installation.
- 6) Utilization of residual dreg, fermented liquor and biogas.

The training session is usually given by an energy organization in China. Invited professionals will arrange workshops to introduce and share required knowledge for using the biogas plant. However, the authors' survey shows that current technical training organized by the government is lecture style without mutual participation, which affects farmers' learning motivation and often results in poor training outcomes.

2) *The Investment In A Biogas Plant And The Financial Support From The Government:* The installation cost of a biogas plant is about RMB 1820 in Gansu province. This will constitute a major obstacle to the utilization of biogas if no subsidy is provided to local farmers, for their average annual income in poverty regions in Gansu province is about RMB 1000 per capita. Hence the biogas projects are hardly implemented due to their financial problems and other obstacles [13]. However, the Chinese government takes both financial and policy measures to support extension of the biogas plant. For instance, in some regions RMB 1500 is subsidized to farmers at present. The farmers pay RMB 320 and provide labor for construction (see table 1). Compared to Sweden and other regions in the world, the Chinese government has provided great incentives for the development of biogas plants, which exerts a positive effect on controlling greenhouse gas emission [14]. However, it is not easy to compare such biogas plant to the price of commercial fuels which is a crucial factor for the implementation of biogas plant in Europe [15].

3) *More Encouragements From The Chinese Government:* Besides the financial support, the Chinese government also takes other steps to popularize the biogas plants with the following methods:

1) Guided tour to a model biogas plant. Full financial support will be offered for a model plant installation in every village where biogas has never been introduced. After the biogas plant is built up, the villagers are organized to visit and experience all the differences between their tradition styles and the biogas system, including the kitchen without dirty smoke. They can compare their daily fuel with biogas, which can further help make their own decisions for constructing biogas plants.

2) Guided tour to biogas plants in other villages. A great number of biogas plants have been completed in some villages. Farmers are organized to visit there and people who have already had biogas plants share their experience with the visitors.

The enormous contrast between the traditional kitchen and the one with biogas will impress the farmers deeply. Other benefits such as reduction in time for collection of fuel materials and increase leisure time also play an important role in convincing the farmers of installing a biogas plant, let alone the improvement in the living standard.

4) *The Role Of Local Communities*: Most of the training sessions are held in village-level communities and farmers are free to decide whether or not to attend. It is the community's responsibility to invite professionals to introduce biogas knowledge to the local people. The present study and past experience both indicate that the ideal size of a study group is 3 to 5 people, which offers farmers enough opportunities to discuss with and learn from each other.

5) *The Delivery Of Related Publications*: A brochure on the biogas construction and management is delivered to each family for free. However, most farmers in Gansu province do not have a good education background, and the data collected from survey has shown that more than 90% of the villagers are illiteracies in some remote poor villages. Most educated farmers have only finished the third year in primary school. As a result, the five-part booklet is mainly composed of picture illustrations to help those farmers better understand:

- 1) The construction techniques of biogas plant.
- 2) The raw materials for biogas and the basic condition required.
- 3) Knowledge about the utilization of biogas and safety instructions.
- 4) Frequently-met malfunctions of the plant and maintenance methods.
- 5) Integrated utilization of residual dreg and fermented liquor.

IV. CONCLUSION

According to the utilization situation of the improved biogas plant in Jingyuan Country, Gansu Province, it has been found that the improvement engineering design of biogas plant can significantly improve the reliability and reduce the maintenance procedures. A small, but smart improvement could bring about a big change. Farmers are able to save more cash by using biomass energy, and earn more by seasonal and permanent migrant work. Moreover, farmers with a biogas plant are more healthy and freed from labor intensive extraction work. With government's financial and policy support, biogas plants have increasingly played important roles in improving energy structure in rural China than ever before.

At the same time, training is necessary for both maintaining biogas plants and making good use of slurry. In the case study, farmers have been organized together to learn and share their experience of properly using biogas plants. Participation training and community-based demonstration of biogas knowledge would facilitate more farmers to adopt biogas plants because less-educated farmers are good at leaning through both participatory approaches and picture-based demonstration materials.

In sum, wide range of pilot biogas plants have been established in Jingyuan County and other similar regions in semi-arid regions of northwestern China since 2002, many of which

have achieved great success. The family-size biogas is adaptable to the cold winter in Gansu province. The government-supported system can effectively change the energy consumption pattern in rural area, and reduce deforestation. The living expenses of farmers have been enormously decreased by use of biogas and farmers' income increases greatly. With use of the improved biogas plants in engineering design, the family-size biogas plant has an enormous prospect in Gansu province, China, and other places with similar environment. Furthermore, the authors will keep exploring more effective measures to increase inside temperature of a digester so as to make best use of biogas in semi-arid and cold regions of China.

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TABLE I
 COST OF CONSTRUCTION AND INSTALLATION FOR A DIGESTER OF 10m³

Name Of Component	Unit	Cost(RMB)
Bricks	1000pieces	200
Cement	1.5tons	500
Steel	20kilos	120
Inlet PVC pipe(D=200mm)	4 meters	120
Circumfluence PVC pipe (D=110mm)	6 meters	120
Outlet PVC pipe (D=90mm or 110mm)	2 meters	40
Labor for digging the pit	1 man(3 working days)	120
Labor for construction	5 man(3 working days)	600
Total cost	-	1820
Government Subsidy	-	1500
Net cost	-	320

Note:USD100=RMB683.

TABLE II
 CAPACITY OF THE JINGYUAN BIOGAS PLANT AT AMBIENT TEMPERATURE

Temperature(°C)	capacity(m ³ /24hrs)
-15-10	0.5
-10-5	0.8
-5-0	1.0
0-8	1.2-1.5
8-20	1.5-1.9
20-30	1.9-2.5
30-40	2.5-3.2
40	3.8

TABLE III
 RELATIVE DATA OF DIGESTING

Raw material	Carbon (%)	Nitrogen (%)	C:N	Digestion time (days)
wheat stalk	46	0.53	87:1	Over 90
Maize stem	42	0.63	67:1	90
leaves	41	1.00	41:1	90
grass	14	0.54	26:1	60
Fresh pig dung	7.8	0.60	13:1	60
Fresh human dung	2.5	0.85	3:1	30
Fresh horse dung	10	0.42	24:1	90
Fresh cattle dung	16	0.55	29:1	90

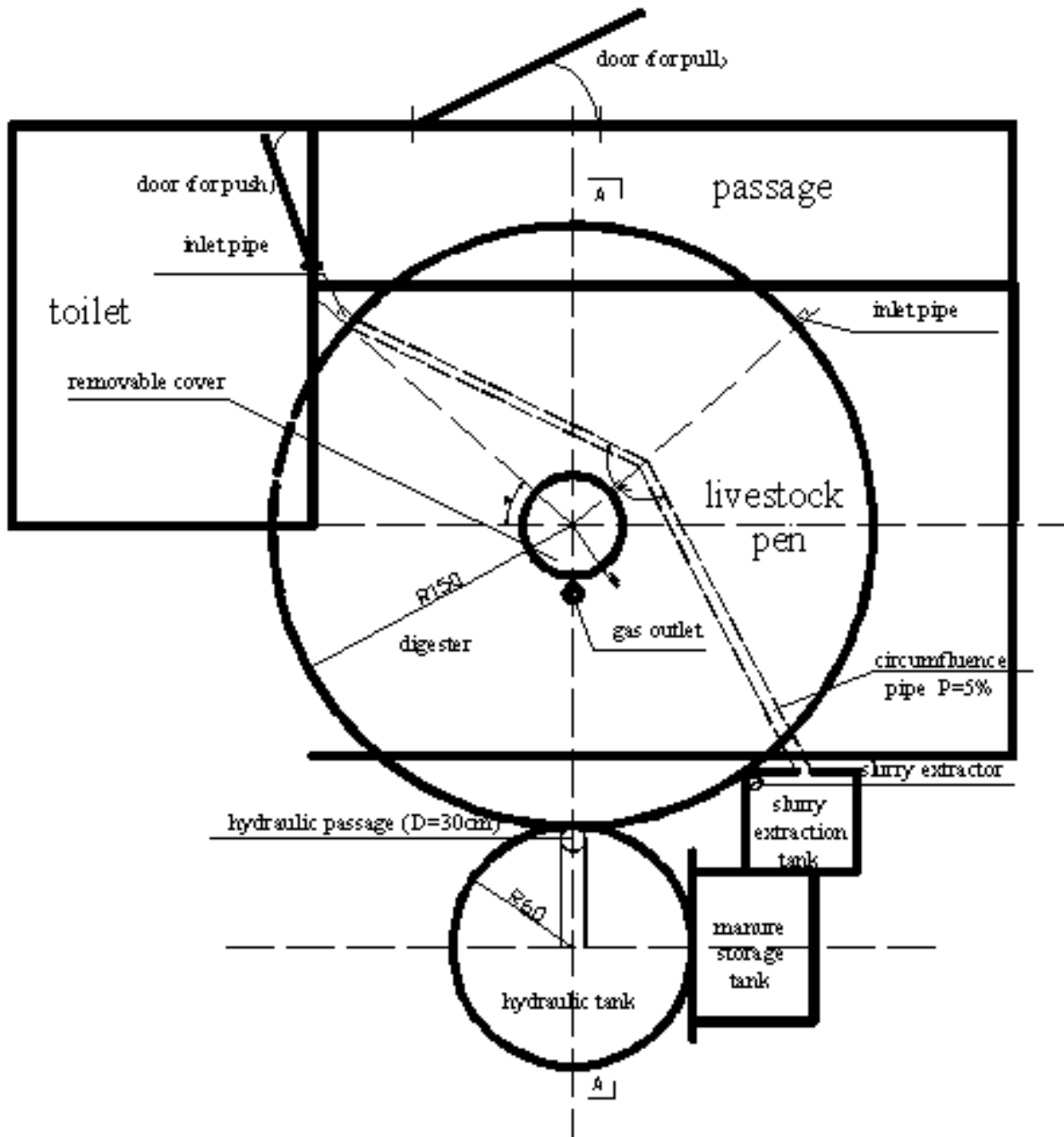


Fig.1 General Layout Plan Of The Renovated Biogas Plant

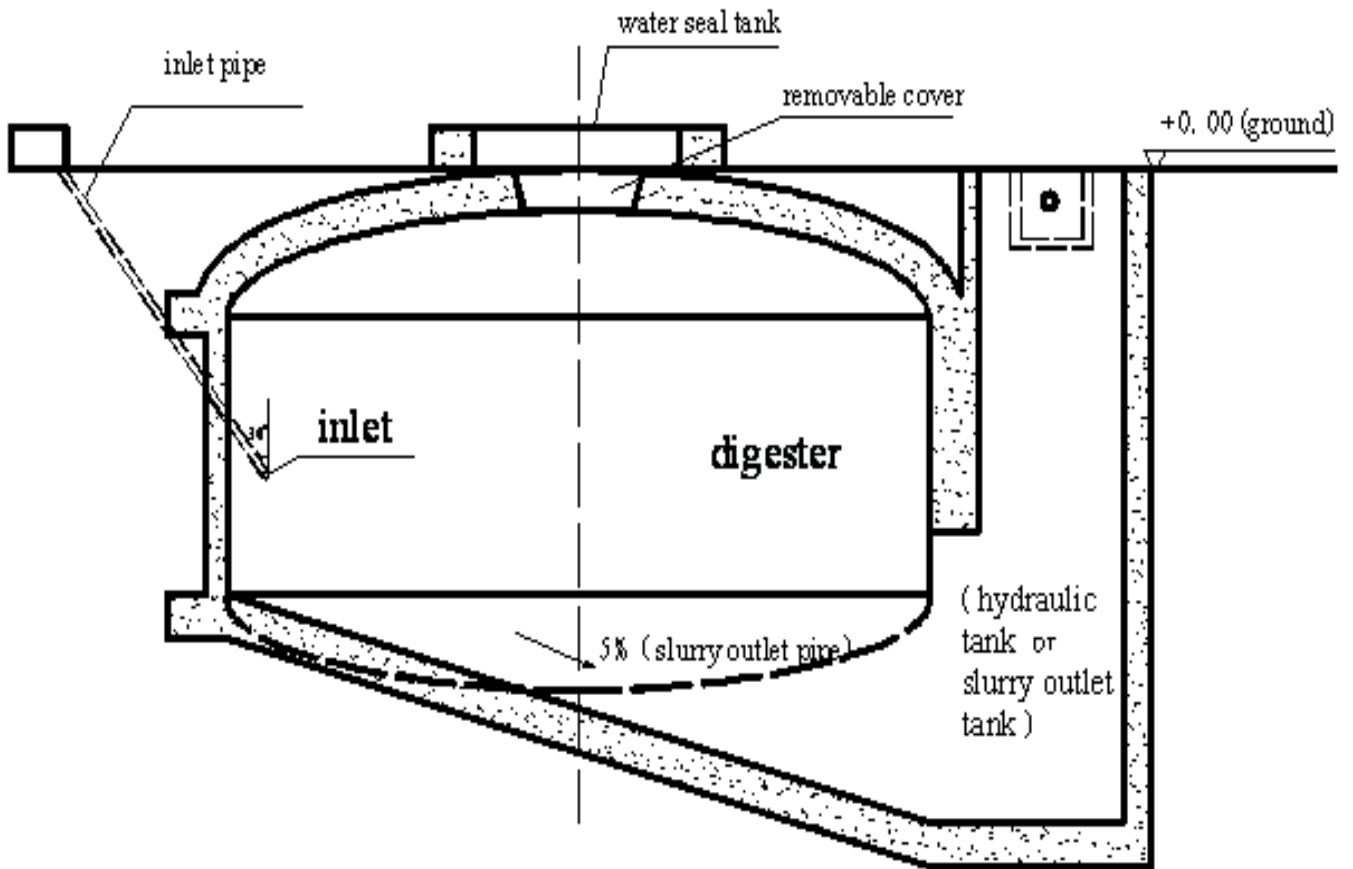


Fig.2 Longitudinal Diagram Of The Traditional Biogas Plant

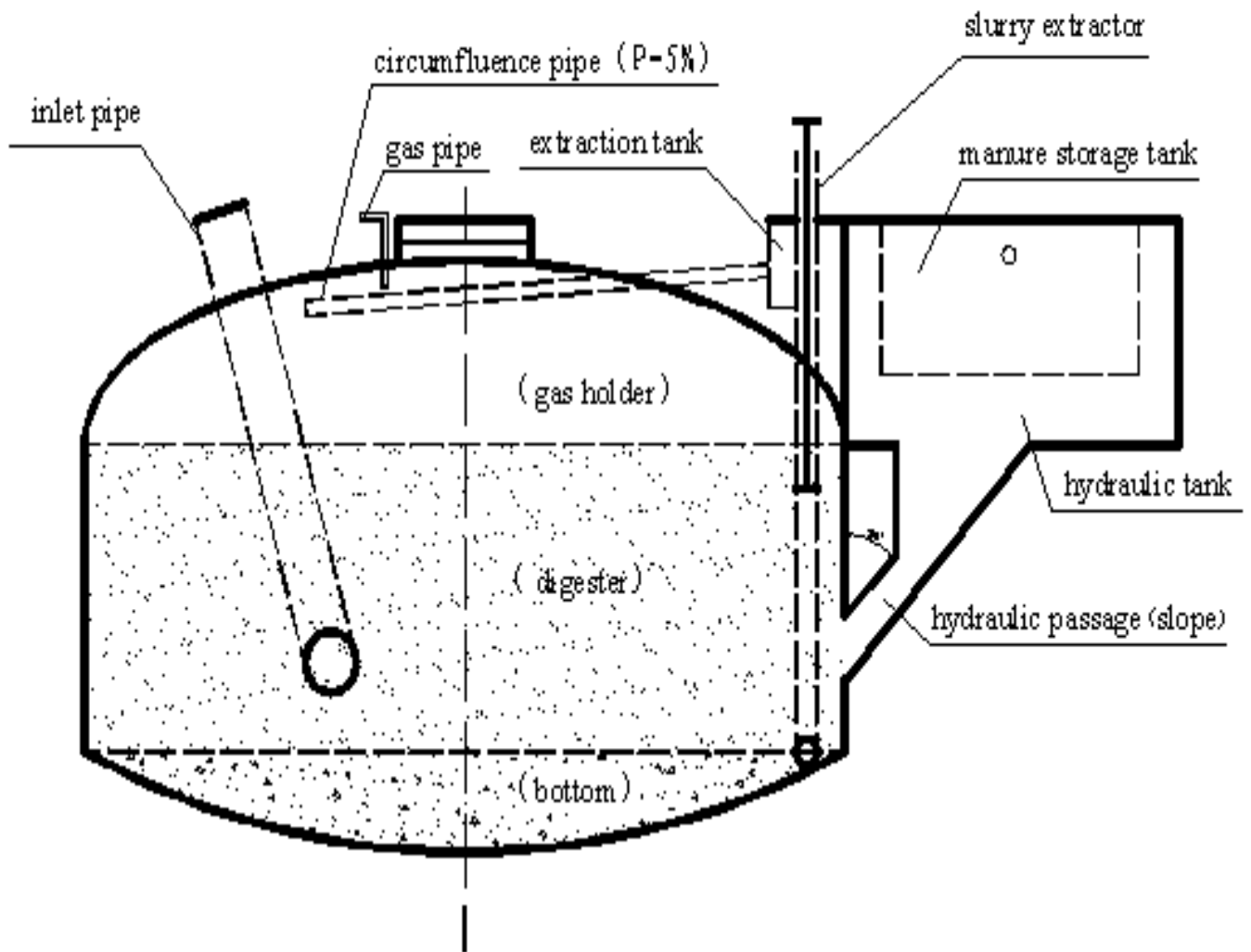


Fig.3 Longitudinal Diagram Of The Renovated Biogas Plant