Biogas technology of complete mixed fodders with application of absorption heat pump

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Abstract. The biogas technology of complete mixed fodders with application of ab-sorption water-ammonia heat pump (AWHP) is proposed. Involvement of ABTN in the technology allowed to prepare high- and low-potential energy carriers and provide stability of temperature regimes of the processes of anaerobic digestion of substrates at biogas production, moisture-heat treatment of grain with superheated steam, micronisation of grain flakes, drying and cooling of complete mixed fodder. Moisture extraction from biogas was carried out in a two-section apparatus with alternate operation of sections in the modes of freezing and regeneration. Absorption of carbon dioxide from the initial biogas was carried out by cooled water obtained by means of regenerative heat exchange with intermediate refrigerant, which was used as tosol. In a two-column catalytic desulphurisation reactor continuous desulphurisation of biogas was carried out by adsorption method using iron oxide as adsorbent. Variable mode of work of columns of the catalytic reactor provided continuity of process of chemical binding of hydrogen sulphide with adsorbent and regeneration of adsorbent by blowing with atmospheric air. Functioning of ABTN for generation of alternative energy was carried out from heat recovery of superheated steam supplied from the steam generator to the boilers. Ammonia condensation heat in the condenser of ABTH was effectively used to stabilise anaerobic digestion of substrates when warm water was supplied to the heating jacket of the bioreactor.

1 Introduction

In 2022, a new federal project 'Closed Cycle Economy' was launched in Russia. The initiative is aimed at fulfilling the task set by the President of the Russian Federation: to halve the volume of all waste and reduce its negative impact on the environment by 2030. The Government of the Russian Federation has formulated the task - to develop and introduce new effective and cost-effective technologies and technical means of organic waste processing with their maximum involvement in the closed cycle economy [1-3].

The implementation of plans to develop the agro-industrial complex (AIC) and increase the number of livestock can lead to an increase in the volume of waste up to 1.2 billion tonnes. The annual damage from agro-industrial complex waste in Russia is estimated at 450 billion rubles, in particular, due to the pollution of water resources. Currently, more than 2 million hectares of land in Russia are used for manure storage [4]. It has been established [5] that the production of 1 tonne of mixed fodder for young farm animals consumes from 300 to 500 kWh/t of electricity and about 300-400 m3 of process steam. Obtaining biogas can fully cover the energy needs for the production of mixed fodder, and the process of anaerobic fermentation when obtaining biogas will allow to process the wastes of livestock complexes into non-toxic organic fertilisers, which can be further used in agriculture [6-10].

Scientists of the All-Union State University of Informatics and Technology (VGUIT), the All-Russian Research Centre for the Compound Feed Industry and industry specialists are constantly working to improve biogas technologies in fodder production [5, 11-14].

The aim of this work is to develop a biogas technology of complete mixed fodders with the use of absorption water-ammonia heat pump (abtn), providing increased energy efficiency through recovery and utilisation of secondary energy resources with the return of low-potential energy into a closed thermodynamic cycle.

2 Methods and materials

At development of biogas technology of complete mixed fodders with application of ABTN the balance method of distribution of energy flows in combination with innovative methods directed on reduction of specific energy consumption at high quality of the received mixed fodder is used.

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The scheme of biogas technology of complete mixed fodders complete with ABTN includes (Fig. 1): hoppers for storage of grain raw material 1; magnetic separator 2; humidifying machine 3; grain tempering hopper 4; steaming machine 5; microniser 6; equipped with gas infrared heaters with burners; roller conditioner 7; hopper for storage of protein-vitamin additives and premixes 8 and hopper for storage of mineral raw materials (zeolite, bentonite, limestone, chalk) 9; dryer-cooler 10 with drying and cooling sections; filling and packing machine 11, storage tanks for solid 12 and liquid substrate 13, conveyor 14, pumping station 15, bioreactor 16 equipped with cavitation unit with internal thermal jacket and stirrer; digested substrate storage 17, gas holder 18, turbo compressor 19; two-sectional apparatus for dehydration of initial biogas with sections 20/1 and 20/2; column for biogas purification from carbon dioxide 21; two-column catalytic desulphurisation reactor with columns 22/1 and 22/2; water regeneration column 23; water collector 24; buffer tank for accumulation of purified biogas 25; compressor 26; steam generator 27 with burners 28; ABTN including boilers 29 with rectifier 30, deflegmator with coil 31, condenser 32, evaporator 33, absorber 34, heat exchanger 35; thermostatic control valves 36, 37, recirculation pumps 38, 39; regenerative heat exchanger for water heating 40; regenerative heat exchanger for water cooling 41; tosol collector 42; mixers 43, 44; 45; flow distributors 46, 47, 48, 49, 50, 51; 52; intermediate water collector 53, pumps 54, 55, 56, 57, 58, 59; regenerative heat exchanger for air heating 60; regenerative heat exchanger for air cooling 61; fans 62, 63, 64, 65; material and heat flows: 1. 0 - grain, 1.1 - moistened grain; 1.2 - steamed grain; 1.3 - micronised grain; 1.4 - grain flakes; 1.5 - mixture of protein-vitamin additives, premixes and mineral additives (chalk); 1.6 - complete mixed fodder; 1.7 - dried complete mixed fodder; 1. 8 - packaged mixed fodder; 2.0 - solid substrate; 2.1 - liquid substrate; 2.2 - fermented substrate; 2.3 - initial biogas; 2.4 - dried biogas; 2.5 - biogas purified from carbon dioxide; 2.6 - desulphurised biogas; 2.7 - purified biogas; 3.0 - superheated steam; 3.1 - low potential steam; 3. 2 - water from snow coat defrosting; 3.3 - condensate; 3.4 - chilled water; 3.5 - carbon dioxide enriched water; 3.6 - heated water; 3.7 - purified water; 3.8 - carbon dioxide; 4.0 - tosol; 5.0 - ammonia vapour, 5.1 - liquid (condensed) ammonia; 5.2 - vaporised ammonia; 5. 3 - strong water-ammonia solution; 5.4 - weak water-ammonia solution; 6.0 - recycled water; 7.0 - atmospheric air; 7.1 - heated air, 7.2 - cooled air; 7.3 - exhaust air; 8.0 - exhaust gases; 8.1 - exhaust gases; 8.2 - warm water.

Initial grain raw material from grain hoppers 1 through magnetic separator 2 is fed to humidifying machine 3 until reaching humidity of 20-25 %. The moistened grain is sent to the hopper for dehumidification of grain 4, and then to the steaming machine 5, in which the moisture and heat treatment of grain with superheated steam for 10 minutes at a temperature of 100-150 °C is carried out. Steamed grain is fed into microniser 6, in which for 40-90 s the grain is subjected to infrared heating at a temperature of 95-125 ° C and the incident flux density from the radiation of infrared heaters 16.3-20.5 kW/m^2.

Micronised grain is passed through the rollers of the conditioning machine 7 with a gap between the rollers of 0.40-0.55 mm. The obtained grain flakes are mixed with a mixture of protein-vitamin additives, premixes and chalk in the mixer 46 to obtain full feed.

Full-rational mixed fodder is fed to the dryer-cooler 10 and dried at a temperature of 80-90 oC and the speed of the drying agent 0.4-0.7 m/s to a humidity of 8-9 %, then cooled to ambient temperature and then sent to the packing and packaging machine 11.

To realise temperature regimes of technological processes, purified biogas obtained by digestion of liquid and solid substrates is used as the main energy carrier.

Substrates from tanks 12, 13 are mixed in the mixer 43 and discharged into the bioreactor 16 equipped with a cavitation unit, an internal thermal jacket and a stirrer. Optimal conditions for anaerobic digestion of substrates in the temperature range of 35-70 °C with maximum biogas yield of 95-98 % are established.

The digested substrate from the bioreactor is discharged to the storage 17, and the obtained initial biogas is sent to the gas holder 18, from which turbo compressor 19 through the flow switch 46 is fed at a pressure of 2 MPa to the section 20/1 of a two-section apparatus for biogas drying, operating in the mode of freezing of moisture. In the same section by means of synchronised operation of the actuators of the dampers is fed tosol with a temperature of minus 12 ºC. On the cooling surface of the section operating in the moisture freezing mode at the temperature of minus 10 ºC, biogas reaches the ‘dew point’ by means of recuperative heat exchange with tosol and the moisture contained in biogas condenses into a snow coat. At the same time, the section of the two-section apparatus for natural gas drying 20/2 operating in the regeneration mode is disconnected from the refrigerant recirculation circuit and defrosted by the exhaust superheated steam supplied through the flow distributor 47 from the boilers 29. Switching of sections of the two-section biogas drying apparatus 20/1 and 20/2 from the moisture freezing mode to the regeneration mode and vice versa, as well as the flows of tosol and saturated steam is carried out according to the moisture content of biogas, the current value of which should not exceed 9 mg/m^3.

After drying, the biogas is directed to column 21, where carbon dioxide is absorbed from the initial biogas with cooled water to a carbon dioxide content of 11% vol.

Preparation of chilled water is carried out in the recuperative heat exchanger 41 by heat exchange with tosol. In this case, the water enriched with carbon dioxide is removed from the column 21 by pump 54 and together with the water formed during defrosting of the section of the two-sectional apparatus, is supplied to the recuperative heat exchanger 40, where it is heated to a temperature of 50-60 ºC by heat exchange with the exhaust gases from the microniser, providing evaporation of carbon dioxide from the water in the column 23.

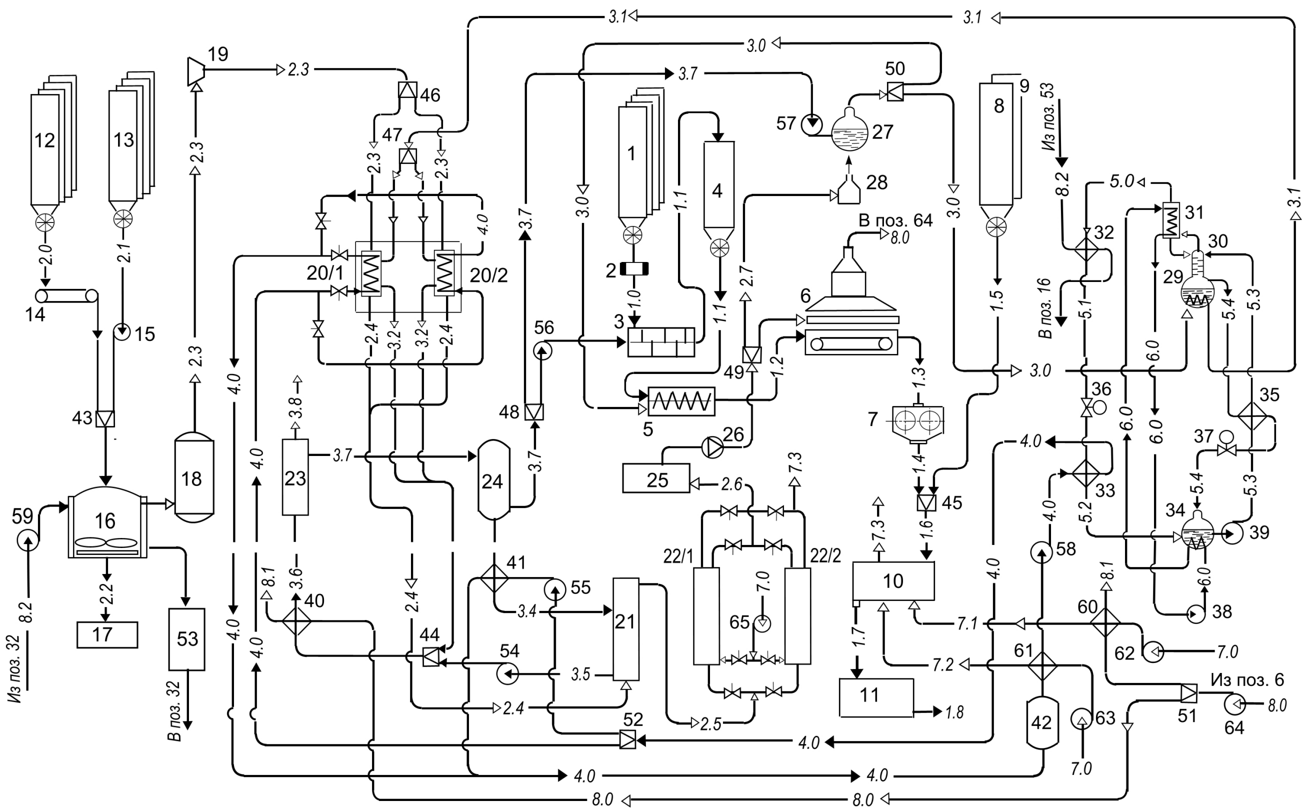

Figure 1. Schematic diagram of biogas technology of complete mixed fodder complete with absorption water-ammonia heat pump

Water purified from carbon dioxide is first discharged into the water collector 24, and then pumps 56 and 57 are supplied respectively to the humidifying machine 3 and to replenish the water level in the steam generator 27 to form a closed cycle.

After extraction of carbon dioxide biogas from column 21 is fed into one of columns 22/1 and 22/2 of two-column catalytic desulphurisation reactor, in which continuous desulphurisation of biogas is carried out by adsorption method to the content of hydrogen sulphide (H_2S) 20 mg/m3 using as adsorbent iron oxide (Fe_2O_3) with humidity of 5 %.

Variable mode of work of reactor columns is carried out: in column 22/1 there is a process of chemical binding of hydrogen sulphide with adsorbent, and in column 22/2 - regeneration of adsorbent by blowing with atmospheric air by fan 62 with exhaust air output to atmosphere.

Adsorption method of hydrogen sulphide removal consists in formation of sulphites at interaction of hydrogen sulphide with iron oxide:

$$Fe_2O_3 \cdot 3H_2O + H_2S \rightarrow Fe_2S_3 + 6H_2O$$

During adsorbent regeneration elemental sulphur is formed, depositing on the surface of iron oxide:

$$Fe_2S_3 + O_2 + 3H_2O \rightarrow Fe_2O_3 \cdot 3H_2O + 3S$$

After each regeneration the sorption capacity of iron oxide decreases on average by 15 %, which necessitates regular replacement of the spent adsorbent and, consequently, variable operation mode of the columns.

Purified biogas from the catalytic desulphurisation reactor is discharged to the buffer tank 25, is subjected to compression compression in the compressor 26 and under pressure of 1.2 MPa is supplied for combustion to the burners of the microniser 6 and burners 28 of the steam generator 27.

During combustion of purified biogas in the burners of the steam generator continuous generation of superheated steam with a temperature of 150 oC is carried out and its supply to the steamer 5 for moisture and heat treatment of grain

Condensation heat of ammonia in condenser 32 of ABTN is transferred to water, which is continuously fed by pump 59 into the thermal jacket of bioreactor 16, providing optimal conditions for anaerobic digestion of substrates.

The superheated steam obtained in the steam generator 27 is used as a source of energy for the operation of the ABTN, which includes boilers 29 with rectifier 30, coil and deflegmator 31; condenser 32; evaporator 33, absorber 34; heat exchanger 35; thermostatic control valves 36, 37, recirculation pumps 38, 39.

Superheated vapour from the steam generator 27 is directed to the boiling coil 29, in which water-ammonia solution is evaporated at a temperature of 140 °C. The mixture of the resulting water vapour and ammonia passes through the nozzles of the rectifier 30, which is sprayed with a strong water-ammonia solution supplied to the boiling coil 29 by the transfer pump 39 from the absorber 34. Part of the water is entrained by the flowing solution along the nozzles of the rectifier 30, and the concentration of ammonia vapour increases. Concentrated ammonia vapour is discharged to the deflegmator 25, the residual water condenses and flows down the nozzles of the rectifier 30 into the boiling pot 29.

Dried ammonia vapour from deflegmator 24 is directed to condenser 32 and condensed at a temperature of 40 - 60 ° C, after which the flow of liquid ammonia is throttled in the thermostatic control valve 36 to a pressure of 0.26 MPa and a temperature of minus 14 oC, from which it boils in the evaporator 33.

The vaporised ammonia from the boilers 29 is fed to the absorber 34 through the regenerative heat exchanger 35 and thermostatic control valve 37. Absorption of ammonia vapour by weak water-ammonia solution in absorber 34 is accompanied by heat release, which is taken away by recycled water flowing through the absorber coil.

The formed strong water-ammonia solution in the absorber 34 is directed by the recirculation pump 39 to the boilers 29 through the heat exchanger 35. In the heat exchanger 35 the strong water-ammonia solution is preheated, which leads to cooling of the weak water-ammonia solution, providing an increase in its absorption capacity and saving of thermal energy.

Recirculation of recycled water through absorber 34 and deflagmator 30 by recirculation pump 38 allows increasing energy efficiency of the processes of condensation of water vapour in deflagmator 34 and ammonia vapour in condenser 26 and providing removal of absorption heat from absorber 34. The recycled water is not discharged from the recirculation circuit, and there is no need for periodic analysis of water for the presence of ammonia in it.

Waste gases after micronisation with a temperature of 90 oC are directed by a fan 64 through a flow distributor 51 to a heat exchanger for heating water 44, as well as to a heat exchanger 40 for heating air taken from the atmosphere, which is then supplied to the drying section of the dryer-cooler 10 as a drying agent by a fan 63.

The air from the atmosphere by the fan 63 is firstly fed to the recuperative heat exchanger 61 and then to the drying section of the dryer-cooler 10 for cooling the complete mixed fodder before it is fed to the filling and packing apparatus 11.

3 Results and discussion

The proposed biogas technology of complete mixed fodders with the use of ABTN has been tested on the experimental equipment in the production conditions of Research and Production Centre VNII Kombikormovaya Industry (tab. 1).

As an example, the technology of full-forage mixed fodder for rabbits according to the recipe PZK - 92 is considered [20-22]. The price of mixed fodder is 28 rub/kg.

Energy costs for the production of mixed fodder according to the known technology are 19.6 rub/kg, which corresponds to 30% of its cost. At a price for 1 kWh of the consumed electric power on a single-rate tariff 4,45 rub energy costs for reception of 1 kg of mixed fodder make 4,4 kWh or 15840 kJ for 1 kg.

It follows from table 1. that the proposed biogas technology with application of ABTN provides reduction of specific energy consumption by 10-12 % at change of parameters of flowing processes in the area of admissible technological properties of received full feed.

Table. 1. Parameters for production verification of biogas technology

Parameter °C	**Parameter value**		
	Mode 1	**Mode 2**	**Mode 3**
Humidity of moistened grain, %	20,0	22,5	25
Temperature of moisture-heating treatment of grain with superheated steam, °C	100	125	150
Temperature of infrared heating of grain during micronisation, °C	95	110	125
Duration of micronisation process, s	40	65	90
Density of incident flux from radiation of infrared heaters, kW/m^2	16,3	18, 4	20,5
Thickness of grain flakes at conditioning, mm	0,40	0,48	0,55
Drying agent temperature, °C	80	85	90
Speed of drying agent, m/s	0,40	0,55	0,70
Humidity of dried complete mixed fodder, %	9,0	8,5	8,0
Temperature of cooled air, °C	7,0	8,5	10
Temperature of substrates digestion, °C	35	52	70
Temperature of heating of water enriched with carbon dioxide, °C	50	55	60
Maximum biogas yield, %	95	96	98
Specific energy consumption, kJ/kg	13930	14090	14260

4 Conclusion

The reserves of energy efficiency of biogas technology of complete mixed fodders have been realised, in particular:

- involvement of ABTN in biogas technology of complete mixed fodders allows to generate alternative energy for implementation of thermal and heat-mass exchange processes of anaerobic digestion of producers, moisture-thermal treatment of grain with superheated steam, infrared heating of grain flakes, drying and cooling of complete mixed fodder;
- alternate operation of sections of the two-section apparatus for natural gas drying, connected with operative defrosting of the section working in the regeneration mode, creates real conditions for continuous process of obtaining biogas purified from water;
- ABTN operation is carried out from heat recovery of superheated steam supplied from the steam generator to the boilers; due to this fact, energy saving is achieved, which is spent only on the operation of controls and pumps in ammonia recirculation and recycled water circuits;
- ABTN radically reduces the operating costs of industrial refrigeration by utilising an affordable alternative energy source that is cheaper than the cost of connecting and utilising additional electrical capacity;
- chemical desulphurisation of biogas due to the formation of sulphites in the interaction of hydrogen sulphide with iron oxide reduces the corrosive effect on the metal surfaces of gas equipment, the corrosion rate decreases from 0.5 - 1 mm to 0.3-0.4 mm per year;
- provides reduction of specific energy consumption by 10-12 %.

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