Waste water biological purification plants of dairy products industry and energy management

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Abstract. The paper presents results of engineering and economical comparison of waste water biological purification plants of dairy products industry. Three methods of purification are compared: traditional biological purification with the use of secondary clarifiers and after-purification through granular-bed filters, biomembrane technology and physical-and-chemical treatment together with biomembrane technology for new construction conditions. The improvement of the biological purification technology using nitro-denitrification and membrane un-mixing of sludge mixture is a promising trend in this area. In these calculations, an energy management which is widely applied abroad was used. The descriptions of the three methods are illustrated with structural schemes. Costs of equipment and production areas are taken from manufacturers' data. The research is aimed at an engineering and economical comparison of new constructions of waste water purification of dairy products industry. The experiment demonstrates advantages of biomembrane technology in waste water purification. This technology offers prospects of 122 million rubles cost saving during 25 years of operation when compared with the technology of preparatory reagent flotation and of 13.7 million rubles cost saving compared to the option of traditional biological purification. Key words: waste water purification, dairy products industry, energy management

1. Introduction

In the context of regulatory requirements for the quality of treated wastewater, as well as continuous upgrading of production technology in the dairy industry, there is an urgent need for a new acceptable wastewater purification scheme. This new scheme should be based on modern methods of assessing economic efficiency of water supply and disposal technologies. The improvement of the biological purification technology using nitro-denitrification and membrane un-mixing of sludge mixture is a promising trend in this area [1-17].

2. Materials and methods

An engineering and economical comparison of a new construction of waste water biological purification plants for dairy products industry was made through the analysis of three methods of purification:

- Option 1 – reagent flotation and biological purification in MBR (membrane bioreactor);
- Option 2 – biological purification in MBR;
- Option 3 – biological purification in nitro-denitrification aerotanks with horizontal secondary clarifiers and after-purification filters.

Figure 1 demonstrates structural schemes for the options under consideration.
Figure 1. Structural schemes of waste water purification constructions of dairy products industry: a – physical-and-chemical treatment and MBR (Option 1); b – MBR (Option 2); c – traditional biological purification and after-treatment (Option 3); 1 – pressure-tight flotation unit; 2 – reagent unit; 3 – denitrificator; 4 – nitrification aerotank; 5 – membrane basin; 6 – secondary horizontal clarifier; 7 – granular-bed filters.

Parameters of waste-disposal plants of one dairy industry plant are taken as initial data. This plant processes 170 tonnes of milk per day with waste water consumption of 500 m³/day at an average. Source water composition, mg/l: BOD (full) – 1000; nitrogen ammonium – 20; nitrogen nitrate – 20; suspended materials – up to 500. The quality of purified runoff corresponds to fishery water bodies MAC, mg/l: BOD (full) – 3; nitrogen ammonium – 0.4; nitrogen nitrate – 9; suspended materials – up to 3.

Averaging structures, mechanical purification, neutralization and decontamination are the same for all options and have not been taken into account.

The volume of disposal sludge was calculated when it was dehydrated to 80% humidity. The constants defined in studies [18,19,20] were used for calculation of biological purification plants. The methodology presented in Work [21] was used for these calculations. Granular-bed filters are calculated by SNIP (Construction Rules and Regulation) 2.04.03-85.

3. Results
Table 1 presents main technical characteristics of the options being compared. The volume of tanks and vessels includes volumes of flotation units, nitrification aerotanks, membrane basins, secondary clarifiers, after-purification filters, washout water basins.

Costs of equipment and production areas are taken from manufacturers' data. These costs include flotation units of stainless steel, a set of reagents and reagent units, tube flocculators from polyethylene, block-modular biological purification plants from carbon steel with anti-corrosive treatment, air blowers, pumps, sand filters and light metal constructions with mounted technological equipment, automatic systems, heating and ventilation. The cost of membrane cartridges is taken as $40 for 1m² of membrane. Energy cost calculations include technological equipment, heating, ventilation, lighting and control cabinets, together with tariff calculation of 3.44 rub/kWh. The number of service personnel is determined by using the project staff schedules of physico-chemical and biological treatment plants and includes engineering staff workers, technological links and repair team.

The cost of current repairs is 0.5% of the cost of buildings and facilities and 1% of the cost of equipment. In addition to annual costs, there are recurrent expenses for replacing membranes and equipment. The life of the membrane is set according to the data given by leading producers – 10 years. The average life of equipment before replacement (pumps, mixer, air blowers, etc.) is accepted as 7 years. In calculating the cost of reagents, actual expenditures of water purification plants are taken, that is coagulants (75 rub/kg) and flocculants (50 rub/kg).
Table 1. Main parameters influencing the cost of structures and capital costs of the options under analysis

| Name                                      | Unit of measurement | Option 1, FHO ++ MBR | Option 2, MBR | Option 3, Aerotanks + +granular-bed filters |
|-------------------------------------------|---------------------|----------------------|---------------|-------------------------------------------|
| Concentration of silt                    | g/l                 | 7                    | 7             | 3.5                                       |
| Volume of tanks and vessels              | m³                  | 385                  | 641           | 940                                       |
| Granular-bed filters surface             | m²                  | -                    | -             | 3.08                                      |
| Membrane surface                         | m²                  | 1932                 | 1932          | -                                         |
| Construction works                       | thousands, rub.     | 4095                 | 2981          | 3113                                      |
| Equipment                                | thousands, rub.     | 165099               | 146060        | 179754                                    |
| Membranes                                | thousands, rub.     | 5023                 | 5023          | -                                         |
| Other costs                              | thousands, rub.     | 7959                 | 6976          | 6345                                      |
| Total estimated costs                    | thousands, rub.     | 177153               | 156017        | 189212                                    |

Table 2 presents main performance characteristics.

Table 2. Main performance characteristics

| Name                                  | Unit of Measurement | Option 1, FHO ++ MBR | Option 2, MBR | Option 3, Aerotanks + +granular-bed filters |
|---------------------------------------|---------------------|----------------------|---------------|-------------------------------------------|
| Quartz sand                           | t/yr                | -                    | -             | 8.6                                       |
| Ferric chloride                       | t/yr                | 5.7                  | 5.7           | 5.7                                       |
| Lemon acid                            | t/yr                | 0.25                 | 0.25          | -                                         |
| Sodium hypochlorite                   | t/yr                | 0.65                 | 0.65          | -                                         |
| Residue                               | t/yr                | 1518                 | 341           | 564                                       |
| Energy consumption                    | thousand kwh/yr     | 350.4                | 318.5         | 296.8                                     |
| Building development area             | m²                  | 197                  | 259           | 530                                       |
| Maintenance engineers                 | persons             | 14                   | 10            | 10                                        |

Table 3 presents annual operating costs as well as on-recurrent costs divided by their frequency in years.

Table 3. Operating costs, thousands of rubles/year

| Name                                   | Option 1, FHO ++ MBR | Option 2, MBR | Option 3, Aerotanks + +granular-bed filters |
|----------------------------------------|----------------------|---------------|-------------------------------------------|
| Reagents                               | 3925                 | 127           | 94                                        |
| Energy consumption                     | 845                  | 768           | 715                                       |
| Negative impact costs                  | 457                  | 104           | 171                                       |
| Labour expense, including insurance payments | 4264               | 3016          | 3016                                      |
| Current Repairs                        | 1065                 | 945           | 1069                                      |
| Waste disposal charges                 | 456                  | 102           | 169                                       |
Replacement of membranes | 502.3 | 502.3 | -
Replacement of technological equipment | 3363 | 3073 | 2374
Total | 14876 | 8637 | 7608

The analysis of Table 3 shows that Option 3 (the one with traditional biological purification and after-purification plants) has the lowest operating cost. Option 1 (with preparatory reagent flotation and biological purification), in its turn, has the highest cost, this result being the cost of reagents.

The main economic instrument used abroad to reduce losses and increase efficiency of engineering systems is a life-cycle cost analysis. (Lifecycle cost, LCC). This analysis of biological waste-water treatment systems in Russian conditions has been performed by V.I. Bazhenov and N.A. Krasnoshechekova [22]. Life cycle costs are calculated over the life of the service (the calculation period), including construction, purchase and installation of equipment, start-up and setup, all operating costs for the period, up to the cost of liquidating the facility:

$$LCC = C_i + C_e + C_o + C_m + C_s + C_{env} + C_d$$

where $C_i$ – is the capital cost, including the costs of construction work and acquisition of equipment, installation and commissioning; $C_e$ – the cost of energy resources; $C_o$ – current costs; $C_m$ – service and maintenance costs (repair and replacement of equipment); $C_s$ – cost of downtime or loss of productivity (loss of profit); $C_{env}$ – costs of environmental protection and prevention of damage; $C_d$ – cost of recycling, calculation of residual value.

In Formula (2), all costs are expressed in monetary units, where $C_i$ are one-time investments and refer to the base year, while the remaining costs are determined for the estimated time-span of the object’s life cycle. The best option is the one that has the smallest value of LCC.

In economic efficiency calculations, the time factor must be taken into account, leading to the cost of later years by the base year with the help of the discount factor [23]:

$$K_d = \frac{1}{(1+i)^n}$$

where $i$ – is the interest rate in unit fractions, usually taking into account deposit rates of the highest reliability banks; $n$ – is the period of the cast in years.

A similar decision is used in the well-known handbook edited by V.N. Samokhin [24]. This approach is fully correct in case all fixed payments in the future are known beforehand. In this calculation, prices, tariffs, wages, etc. will increase. This can be taken into account by the annual rate of inflation [22]. Therefore, in the comparison of options, each of the N-year costs was cast to the reference year according to the formula:

$$C_n = C_p \left(\frac{1+p}{1+i}\right)^n$$

where $C_p$ – is cost of future period in prices at the time of comparison; $p$ – is the annual rate of inflation, unit fraction.

In the present calculation we take $i = 0.1$ and $p = 0.0644$. The calculated operation life of waste-disposal plants is taken as 25 years, which corresponds to the estimated lifetime of purification constructions of block-modular type. When determining LCC value, $C_i$ refers to the base year and is not discounted. The remaining additive components (2) are adjusted according to Formula (4) for each n-th year, and then summarized. The replacement of membranes is planned in the 10th and 20th years of the calculation period, and the replacement of the technology equipment – in 7th, 14th and 21st years.

4. Discussion

The $C_e$ value includes the cost of electrical and thermal energy. The value of current costs consists of wages, land lease, the cost of reagents, sand loading. The $C_i$ value includes the cost of current repairs,
the planned replacement of the membrane and the process equipment, which are further considered separately. The cost of out-of-service time or Cs performance loss in this calculation is not taken into account, because facilities in question are of equal reliability. The costs of environmental protection and prevention of damage Cenv come from fees for negative environmental impacts of discharges of harmful substances into water objects and placement of a hazard class IV waste – dehydrated active silt and piloto-sludge. Cd does not take into account the costs of the disposal of the objects and their residual value. The results of LCC calculation are presented in table 4 and figure 2.

![Pie charts showing life-cycle cost structure LCC for different options](image)

**Figure 2.** Life-cycle cost structure LCC of biological purification and after-purification of dairy industry plants with new construction options
Table 4. Life cycle costs, thousands rub.

| Name                        | Symbol | Option 1, FHO ++ MBR | Option 2, MBR | Option 3, Aerotanks + granular-bed filters |
|-----------------------------|--------|----------------------|---------------|-----------------------------------------|
| Capital costs               | Ci     | 177153               | 156017        | 189212                                  |
| Cost of energy              | Ce     | 14157                | 12867         | 11991                                   |
| Current costs               | Co     | 137276               | 52680         | 54584                                   |
| Current Repairs             | St1    | 17845                | 15840         | 17914                                   |
| Replacement of membranes   | St2    | 6216                 | 6216          | -                                       |
| Replacement of equipment    | St3    | 84208                | 76958         | 59452                                   |
| Costs of environment protection | Cenv | 7662                 | 1741          | 2862                                    |
| Total                       | LCC    | 444516               | 322320        | 336015                                  |
| Economical effect           | ΔLCC   | 122197               | -             | 13695                                   |

The lifecycle cost analysis shows that Option 1 provides the largest amount of LCC. Option 2 (with biomembrane purification) is the technology with the lowest LCC. The amount of funding here, with account of investment during construction and twenty-five years of operation, is 122.1 million rubles less than costs of Option 1. Option 1 (a traditional biological purification scheme with secondary clarifiers and granular-bed filters) took an intermediate position with a LCC of 13.7 million rubles more than in Option 1.

5. Conclusions
1. An engineering and economic analysis showed that reagent flotation in waste water of dairy plants purification dairy to fishery water bodies standards makes no economic sense: life-cycle costs of the option with physico-chemical and biological purification during 25 years of operation are 122 million rubles more compared with MBR technology (for new constructions at 500 m3/day capacity.)
2. In the same conditions, a biomembrane technology of waste water purification in dairy industry plants costs 13.7 million rubles less compared to traditional biological purification and after-purification through granular-bed filters.

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