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An Integrated Engineering Approach to Wastewater Treatment, Intensification, and Closed-Loop Reuse at Gas Compressor Stations: A Case Study of the Shurtan Oil and Gas Production Department (Uzbekistan)

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Abstract: Gas compressor stations in the oil and gas industry generate significant volumes of wastewater - oil-bearing production effluents, domestic sewage, and surface runoff - whose uncontrolled discharge threatens the scarce water resources of arid regions such as the Kashkadarya Province of Uzbekistan. This paper presents an integrated engineering framework for the treatment, intensification, and closed-loop reuse of such wastewater, using the booster compressor stations of the Shurtan Oil and Gas Production Department as a case study. Three complementary directions are synthesized: (I) multi-stage treatment (mechanical, physicochemical, and sorption) combined with utilization of the recovered oil and sludge; (II) intensification of treatment schemes through coagulation-flocculation, thin-layer settling, and pressure flotation; and (III) modernization of facilities with membrane and sorption technologies and the development of water-reuse systems. Theoretical analysis based on typical performance indicators shows that the multi-stage scheme reduces the oil-product concentration from about 500 to 0.5 mg/L (overall efficiency ≈ 99.9%), that thin-layer settling reduces the footprint by a factor of 2.5-3, and that modernization raises the water-reuse share from 15% to 85%. A closed (zero-discharge) cycle returning the treated water to the recirculating cooling system eliminates discharge to natural water bodies. The proposed framework couples environmental protection with resource efficiency and provides an engineering basis for sustainable water management at gas compressor stations.

Keywords: wastewater treatment; gas compressor station; process intensification; thin-layer settler; membrane treatment; water reuse; zero-discharge; water-body protection; Shurtan

Introduction

Natural gas is a cornerstone of the fuel and energy complex of Uzbekistan, and the Shurtan field in the Kashkadarya Province is one of the country's major hydrocarbon sources. As reservoir pressure declines with prolonged exploitation, booster (gas-compression) stations are used to raise the gas pressure for pipeline transport. The operation of these stations - cooling of technological equipment, separation, condensate removal, and equipment washing - generates several categories of wastewater, the most problematic of which are the production effluents contaminated with oil products, mechanical impurities, and dissolved salts[1].

Discharging such effluents into natural water bodies without adequate treatment is environmentally unacceptable, particularly in the arid climate of the Kashkadarya Province, where fresh-water resources are limited. At the same time, the oil products and sludge contained in the wastewater represent recoverable resources, and the water itself can be reused if treated to a sufficient quality. Consequently, wastewater management at gas compressor stations must address three coupled objectives simultaneously: effective treatment, resource utilization, and water reuse, all while protecting water bodies from pollution[2-3].

Previous studies by the authors examined these aspects separately: the improvement of treatment and utilization systems, the intensification of treatment schemes with water-body protection, and the modernization of facilities with the development of reuse systems. The present paper synthesizes these directions into a single integrated engineering framework and evaluates its combined environmental and resource-efficiency performance for the conditions of the Shurtan Oil and Gas Production Department. The study falls within the scope of specialty 05.09.04 - “Water supply. Sewerage. Structural systems for the protection of water bodies”[4].

Materials and Methods

The object of the study is the sewerage and wastewater-treatment systems of the booster compressor stations of the Shurtan Oil and Gas Production Department. The theoretical basis comprises the normative documents of the water-supply and sewerage field (SP 32.13330; the Uzbek building code ShNQ 2.04.03; relevant GOST standards) and the scientific literature, together with the maximum permissible concentration (MPC) requirements established for effluents discharged to water bodies.

The methodology combines classification of the wastewater streams, construction of a multi-stage treatment scheme, calculation of treatment efficiency from inlet and outlet concentrations, comparison of conventional versus intensified and modernized schemes, and the design of a closed-loop reuse cycle. In accordance with the theoretical nature of the study, the quantitative indicators are adopted as generalized (typical) values that illustrate the relative effect of the proposed solutions rather than site-specific measurements.

Results and Discussion

1. Wastewater sources and characterization

The wastewater generated at compressor stations is divided, by origin and composition, into three groups: production (oil-bearing) effluents, domestic sewage, and surface (storm-water) runoff (Fig. 1). The production effluents have the most complex composition, containing oil products in free, emulsified, and dissolved states, together with mechanical impurities and dissolved salts. Each group requires a different combination of treatment methods, which motivates a staged, multi-barrier approach [5].

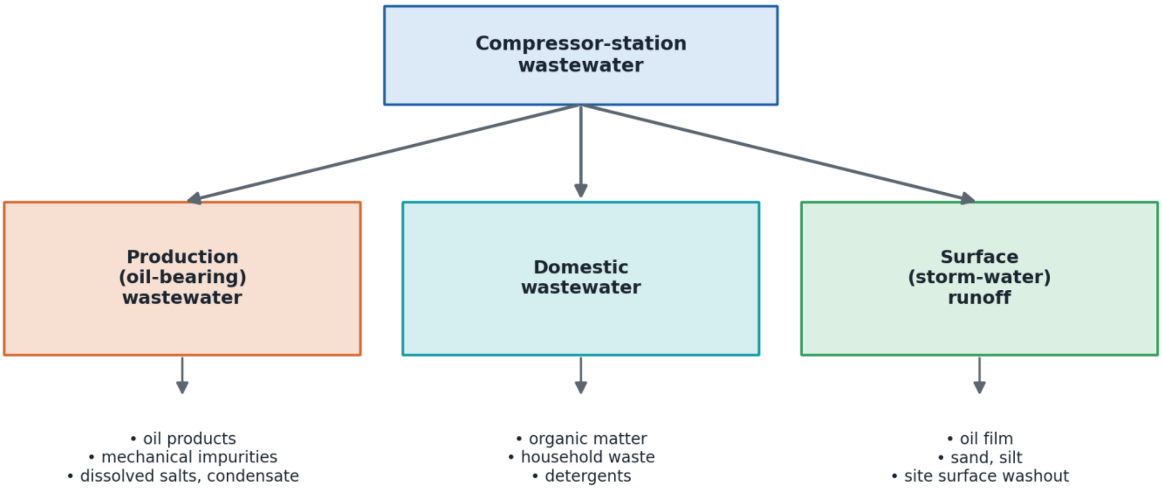

Fig. 1. Classification and composition of compressor-station wastewater.

2. Multi-stage treatment and byproduct utilization

Effective treatment of oil-bearing wastewater is achieved by a multi-stage system comprising three sequential barriers: mechanical treatment (grit chamber and oil trap), physicochemical treatment (flotation), and sorption-filtration polishing. A key feature is that the oil products and sludge separated at these stages are utilized, while the treated water is reused or discharged in compliance with the norms. The treatment methods and their functions are summarized in Table 1[6-8].

Table 1. Treatment methods and residual oil-product concentration.

Treatment method	Target contaminant	Residual oil products, mg/L
Settling / oil trap	free oil, coarse particles	40-50
Flotation	emulsified oil	15-20
Filtration (quartz sand)	fine suspended solids	8-10
Sorption (activated carbon)	dissolved oil products	0.3-0.5

The efficiency of each stage is evaluated from the inlet and outlet concentrations:

$$E = (C_{in} - C_{out}) / C_{in} \times 100\% \qquad (1)$$

where E is the treatment efficiency, %; and C_{in} and C_{out} are the contaminant concentrations at the stage inlet and outlet, mg/L. Across the full scheme, the oil-product concentration decreases from about 500 mg/L at the inlet to about 0.5 mg/L at the outlet - a reduction of more than three orders of magnitude (Fig. 2), corresponding to an overall efficiency of approximately 99.9%[9].

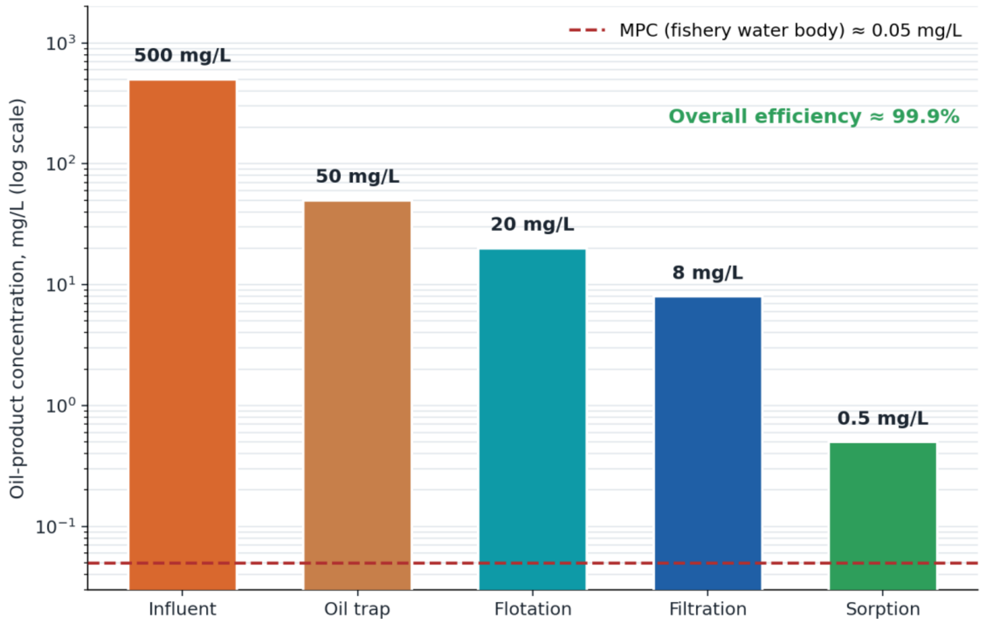

Fig. 2. Oil-product concentration reduction across the treatment stages.

3. Process intensification

Conventional treatment facilities (gravity settlers and simple filters) occupy a large area, fail to remove emulsified and dissolved oil, and operate unstably under variable load. Intensification overcomes these limitations by introducing reagent conditioning (coagulation-flocculation), thin-layer settling, and pressure flotation. The most effective intensification of the settling process is the use of a thin-layer (lamella) settler, in which the flow is divided into thin layers, shortening the particle settling path and accelerating clarification (Fig. 3)[10].

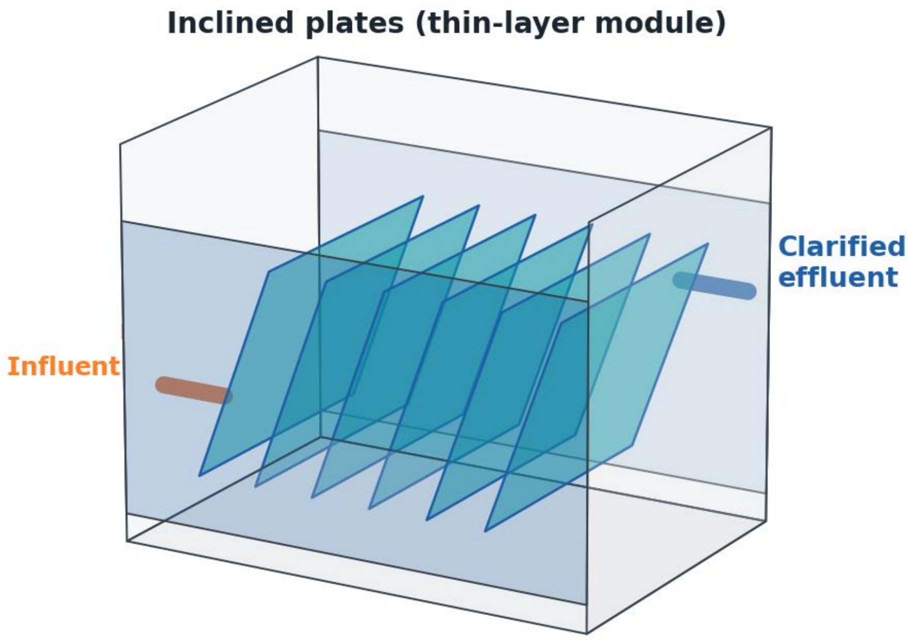

Fig. 3. Three-dimensional view of a thin-layer (lamella) settler.

Compared with a conventional gravity settler of equal throughput, the thin-layer settler requires a footprint 2.5-3 times smaller and reduces the residual oil-product concentration from about 40 to about 15 mg/L. Reagent conditioning enlarges fine and emulsified droplets, and pressure flotation rapidly removes the light oil fraction, so the intensified scheme maintains a stable treatment quality even under the pronounced load fluctuations characteristic of compressor stations[11].

4. Water-body protection

Beyond oil products, the intensified scheme markedly reduces suspended solids and organic pollution (COD). A comparison of concentrations before and after treatment (Fig. 4) yields removal efficiencies of about 99.9% for oil products, 97% for suspended solids, and 95% for COD. These levels render the treated water suitable for discharge in compliance with the norms, or for reuse, and provide reliable protection of water bodies against contamination by oil products, salts, and thermal load[12].

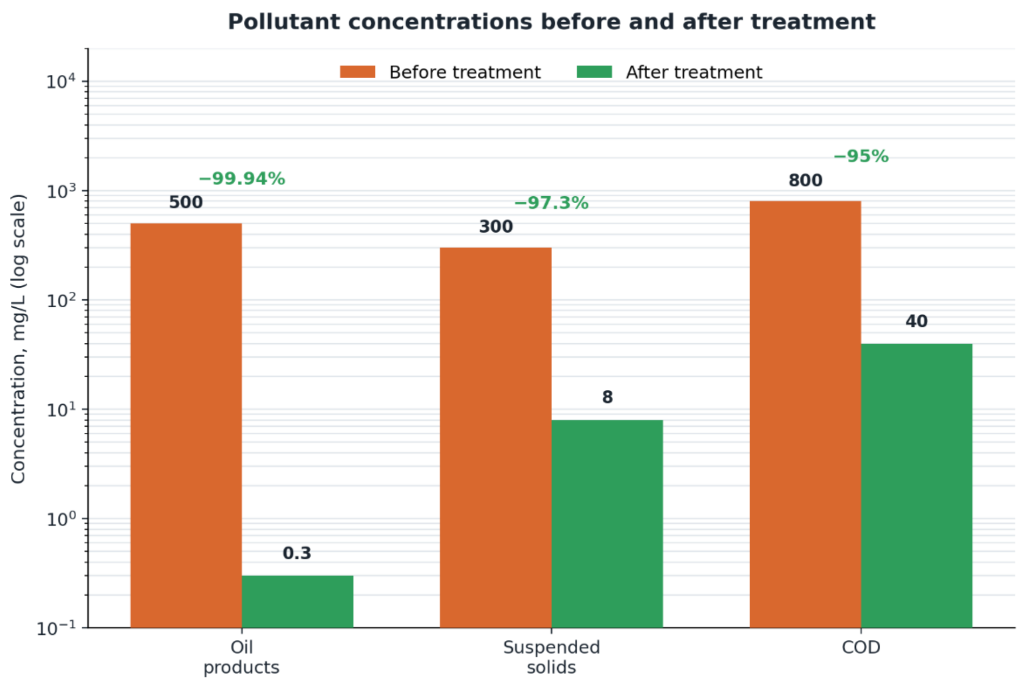

Fig. 4. Pollutant concentrations before and after treatment (logarithmic scale).

5. Modernization and closed-loop reuse

Many existing treatment facilities are physically and morally obsolete, providing only mechanical and simple physicochemical treatment, so that the water-reuse share does not exceed 15%. Their modernization involves introducing membrane (ultrafiltration or reverse osmosis) and sorption deep-treatment technologies. A membrane module separates the wastewater into a permeate (treated water) and a concentrate, achieving a high degree of purification in a compact volume that is well suited to automation (Fig. 5)[13].

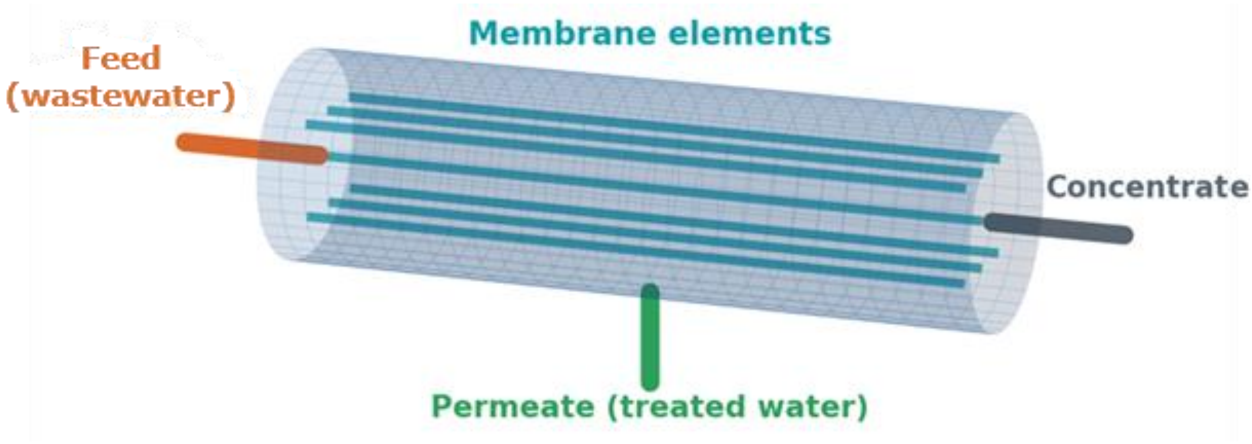

Fig. 5. Three-dimensional view of a membrane treatment module.

Deep treatment brings the treated-water quality to a level suitable for reuse, raising the water-reuse share from 15% to about 85%. The reuse potential is quantified by the water-reuse coefficient:

$$K_r = Q_r / (Q_r + Q_f) \times 100\% \qquad (2)$$

where K_r is the water-reuse coefficient, %; Q_r is the flow of reused water; and Q_f is the make-up fresh-water flow. The ultimate goal is a closed water-reuse cycle in which wastewater from the compressor-station processes is treated, stored, and returned to the recirculating cooling system, with only a small fresh-water make-up added from outside (Fig. 6). This closed (zero-discharge) scheme releases no effluent to natural water bodies[14].

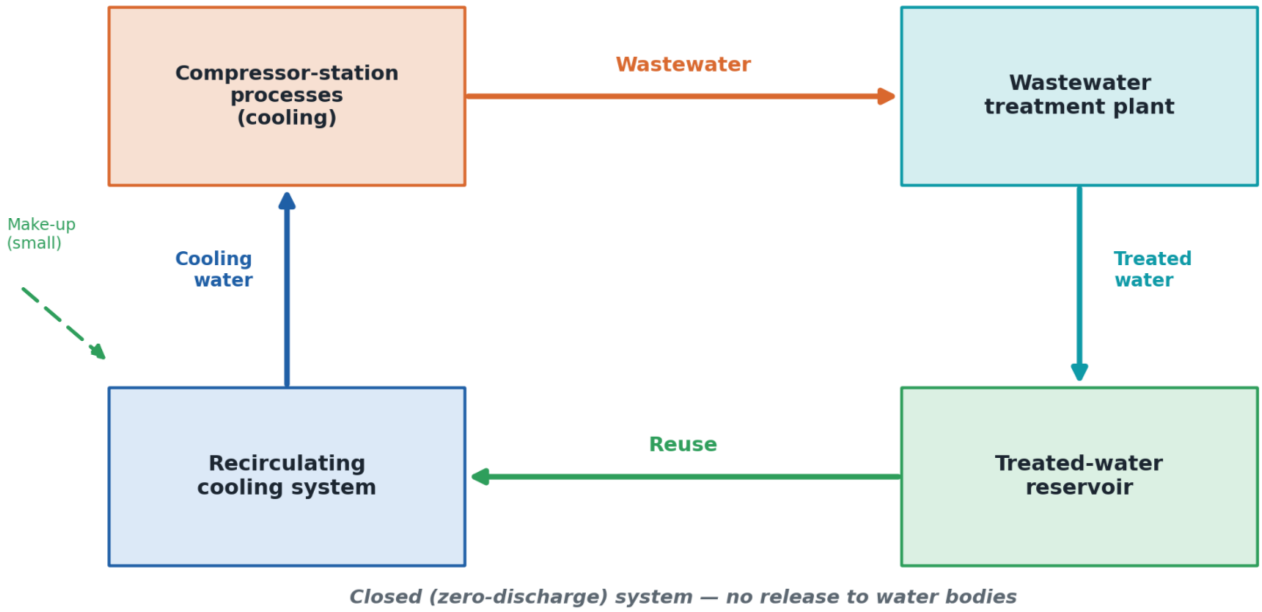

Fig. 6. Closed-loop (zero-discharge) water-reuse cycle.

6. Integrated framework and assessment

The three directions examined above are complementary stages of a single engineering framework (Fig. 7). Mechanical and physicochemical treatment with byproduct utilization form the first pillar; process intensification and water-body protection form the second; and modernization with closed-loop reuse forms the third. Together they constitute a “treatment - utilization - reuse” chain consistent with the principles of zero-discharge production[15].

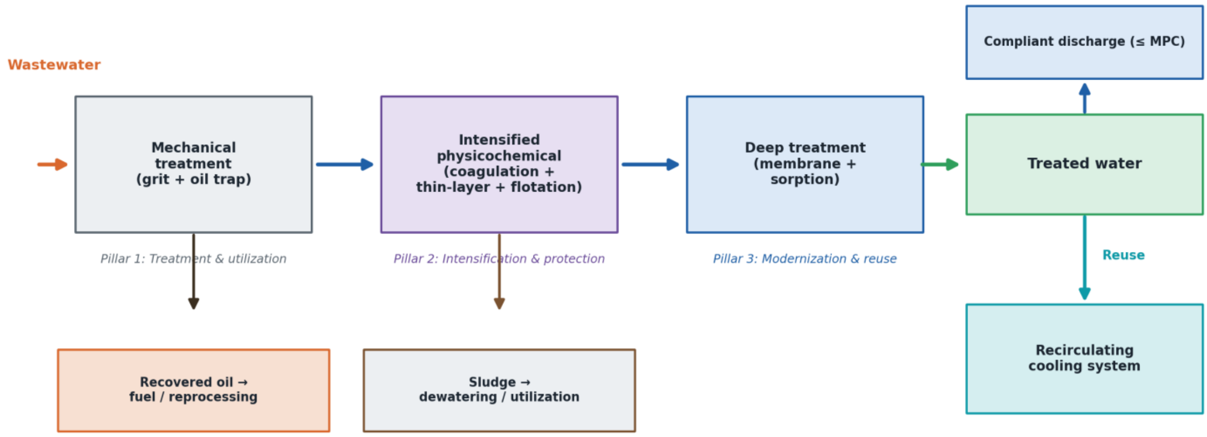

Fig. 7. Integrated engineering framework: treatment - intensification - utilization - reuse.

The combined effect of the framework is summarized in Table 2. The integrated approach improves every key indicator relative to a conventional facility. Economically, the reduction of fresh-water consumption and discharge charges, together with the recovery of oil products, ensures a rapid payback; environmentally, the elimination of discharge protects scarce water resources and the receiving water bodies[16].

Table 2. Conventional versus integrated (intensified and modernized) approach.

Indicator	**Conventional facility**	**Integrated approach**
Treatment stages	mechanical + simple p.-c.	mechanical + intensified p.-c. + membrane + sorption
Residual oil products	15-40 mg/L	< 0.5 mg/L
Footprint of settling	large	2.5-3 times smaller
Water-reuse share	≤ 15%	≈ 85%
Discharge to water bodies	present	none (zero-discharge)

Conclusions

1. Wastewater at the Shurtan gas compressor stations comprises three groups - production (oil-bearing), domestic, and surface - of which the oil-bearing production effluents have the most complex composition and require multi-barrier treatment.

2. A multi-stage scheme combining mechanical, physicochemical, and sorption treatment reduces the oil-product concentration from about 500 to about 0.5 mg/L (overall efficiency ≈ 99.9%), while the recovered oil and sludge are utilized as resources.

3. Intensification by thin-layer settling, coagulation-flocculation, and pressure flotation raises the treatment quality (≈ 97% for suspended solids and ≈ 95% for COD) and reduces the settling footprint by a factor of 2.5-3, thereby protecting water bodies.

4. Modernization with membrane and sorption technologies raises the water-reuse share from 15% to 85%; a closed (zero-discharge) cycle returning the treated water to the recirculating cooling system eliminates discharge to natural water bodies.

5. The proposed integrated framework couples environmental protection with resource efficiency and provides an engineering basis for sustainable water management at gas compressor stations.

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