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Adaptive Renovation of Centrifugal Separators: A Computational–Experimental Methodology for Optimizing Gas-Dynamic Regimes without Capital Expenditure

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Abstract

The methodology proposes an approach to the adaptive renovation of centrifugal multicyclone separators during declining production, without capital expenditure or hot work. The problem is demonstrated to be relevant, driven by the mismatch between gas-dynamic regimes and apparatus geometry, the growth of liquid carryover, and the risk of catastrophic failure of compressor equipment. The objective of the study is to develop and verify a computational–experimental procedure for selecting the active separation area by selectively plugging part of the centrifugal elements to maintain the operating point within the zone of maximum efficiency. The scientific novelty lies in introducing the efficiency triangle concept (velocity–pressure–design), using modified similarity correlations to determine critical velocities, and combining isokinetic probing with algorithmic tray configuration, implemented as a Python module. It is shown that application of the methodology makes it possible to restore the regulatory level of carry-over (<5 mg/m^3), extend the service life of separation equipment, and reduce total costs by eliminating the need for separator replacement, with the intervention cost being less than 1 % of the price of a new separator. The methodology is intended for engineering and technical personnel at gas production and gas processing enterprises, as well as for design and service organizations involved in modernizing integrated gas treatment units.

Keywords: *Adaptive Renovation, Multicyclone Separator, Centrifugal Separation, Gas-Dynamic Optimization, Critical Velocities.*

INTRODUCTION

The operation of gas and gas-condensate fields is a dynamic process characterized by continuous changes in the thermodynamic properties of the produced fluid. At the initial development stages and during the plateau production period, process equipment, including inlet and low-temperature separation blocks, operates within design limits, ensuring a high degree of gas purification from liquid droplets and solid impurities. However, as the field transitions to the decline stage, significant decreases in wellhead pressure and healthy flow rate are observed. This leads to a fundamental mismatch between the geometric characteristics of the installed equipment and the actual gas-flow parameters (Shafikov et al., 2024).

In particular, for vertical separators equipped with multicyclone trays, a reduction in gas flow results in a drop in the swirlers' flow velocity in the centrifugal elements. Since the efficiency of inertial separation depends quadratically on velocity, even a slight decrease in velocity can shift the apparatus into an inefficient operating regime. Under these conditions, the centrifugal force generated in the cyclone becomes insufficient to retain the liquid film on the element walls, leading to film breakup and secondary entrainment into the gas stream (Wang et al., 2023).

The consequences of this process extend far beyond the loss of a portion of saleable condensate. Systematic carryover of liquid (water, corrosion inhibitors, hydrocarbons) triggers corrosion–erosion wear of gathering system pipelines, increases the system's hydraulic resistance, and, most critically, poses a direct threat to gas pumping units (GPU) (Wang et al., 2022). Ingress of liquid into the flow path of centrifugal compressors or into the cylinders of reciprocating compressors can cause catastrophic failures, including hydraulic shocks, valve destruction, and rotor unbalance (Wang et al., 2023).

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Traditional methods of solving this problem, complete replacement of separators with vessels of smaller diameter or factory-level internal retrofit (re-traying), require substantial capital expenditure (CAPEX) and prolonged field shutdowns, which are often economically unjustified at the final stage of the asset life cycle (Xiong et al., 2024). In this context, the development of a scientifically grounded methodology for adapting the existing equipment fleet to current operating conditions with minimal operating expenditure (OPEX) and without hot work (welding) is a relevant scientific and technical task of strategic importance for the industry.

The purpose of this work is the development, theoretical substantiation, and practical implementation of a comprehensive methodology for bringing the gas-dynamic characteristics of a multicyclone separator into conformity with the current thermobaric operating conditions. This objective is achieved by controlled modification of the active separation area through selective plugging of part of the centrifugal elements, thereby artificially maintaining the flow velocity in the remaining operating channels within the zone of maximum efficiency.

The object of the study is industrial vertical gas separators equipped with separation trays comprising an array of parallel centrifugal elements (multicyclones) with a diameter of 100–250 mm. This type of equipment is the de facto standard for integrated gas treatment units due to its compact design and high throughput.

The subject of the study is the hydroaerodynamic behavior of two-phase (gas–liquid) flow in the vortex chambers of multicyclones, the regularities of liquid-film formation and stability, and methods for mathematical modeling of separation efficiency boundaries as a function of the medium's physicochemical properties.

A fundamental constraint of the developed methodology, dictated by industrial safety and economic efficiency requirements, is the modernization without dismantling the main tray structure or welding. All design changes must be reversible, carried out using intrinsically safe tools inside the apparatus, and allow reversion to the initial configuration in the event of a process regime change (for example, when new wells are commissioned).

CHAPTER 1. THEORETICAL FOUNDATIONS AND INSTRUMENTAL DIAGNOSTICS

Physics of the Process and Efficiency Boundaries

The efficiency of a multicyclone separator is governed by a complex interplay of inertial, gravitational, and surface forces. The gas–liquid mixture entering the inlet device of the separator undergoes primary separation (gravitational settling of large droplets), after which it is directed to the separation tray (see Fig. 1).

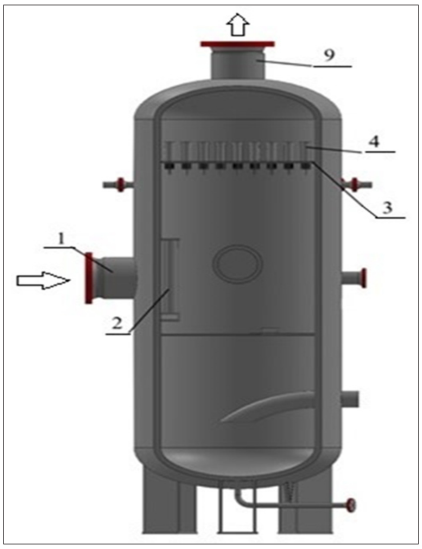

Fig. 1. Separator with separation tray

The gas–liquid mixture enters the separator through nozzle 1 (Fig. 1) and passes through the internal inlet device 2, where primary flow distribution in the vessel and initial separation of liquid and solid impurities occur. Optionally, the partially cleaned gas enters a separation tray 3. There, it is introduced to centrifugal elements 4. These separate the liquid from the gas by centrifugal action. The gas enters the centrifugal element 4 through tangential-type ports 5 (or through an impeller 6 in Fig. 2), where it is imparted with rotation and axial movement.

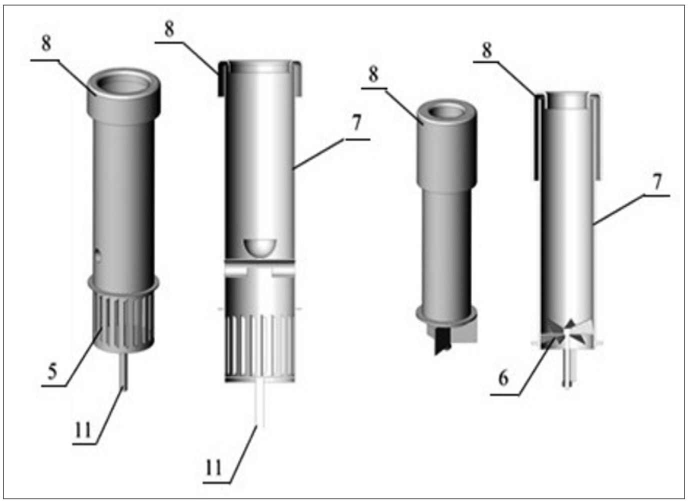

Fig. 2. Variants of centrifugal elements used on the separation tray of the separator

Liquid droplets migrate in the centrifugal flow field toward the walls 7 of the centrifugal element, forming a film that, in an annular–dispersed flow regime, moves vertically toward the droplet collector 8. The gas, separated from the liquid, then flows into the upper part of the vessel and exits through nozzle 9. Thus, the velocity in the centrifugal element 4 is the principal parameter determining its efficiency. The respective velocity values may be obtained both by calculation and by experiment.

In the centrifugal force field, where acceleration may reach hundreds of g, a radial force F_c, directed toward the element wall, acts on the liquid droplet. This force is opposed by the aerodynamic drag force (Stokes drag) to radial drift. Upon reaching the wall, droplets coalesce, forming a liquid film. The flow regime of this film is the determining factor for efficiency. The region inside is called the effective operating zone, bounded by two physical limits.

Lower boundary (inadequate centrifugal force). The film is not forced to the wall by the centrifugal force at low gas velocities. At low gas velocities, the film cannot resist the action of gravity and surface tension forces, which cause it to rupture into large droplets that fall back into the gas.

Upper boundary (film breakup / secondary entrainment). At excessively high velocities, the shear stresses at the gas–liquid interface become critical. Instability waves (Kelvin–Helmholtz waves) form, and droplets are mechanically stripped from their crests and returned to the gas stream's core (Yan et al., 2022).

For the systematic analysis of these processes, the concept of an efficiency triangle is introduced, with vertices: Velocity (process kinetics), Pressure (medium properties, density), and Design (element geometry). The methodology's task is to maintain the operating point within this triangle.

Determination of Critical Velocities (Algorithm for Calculating Boundaries)

The mathematical formalization of efficiency boundaries is based on semi-empirical similarity correlations adapted to the operating conditions of gas field equipment. The key parameter linking medium properties and hydrodynamics is a modified Kutateladze criterion expressed in terms of the critical gas velocity.

Method for determining the maximum critical velocity $W_{max.cr}$

The maximum velocity $W_{max.cr}$, corresponding to the onset of intensive secondary entrainment, is determined from the balance between gas dynamic head and surface-tension-driven retaining forces. The calculation is performed using the following formula:

$$W_{max.cr.} = T_s \cdot \sqrt[4]{\frac{g \cdot \sigma_K}{\rho_p}}$$

where

T_s = 12.0 is an empirical coefficient characterizing structural transformations in the gas–liquid flow at the film-breakup boundary. The value 12.0 is obtained from extensive experimental data processing for standard multicyclones with diameters of 100–150 mm.

$\sigma_к$ is the surface tension of the liquid at the gas interface under operating conditions (N/m). It is essential to account for the fact that dissolved gases and surfactants (e.g., methanol) reduce $\sigma_к$, thereby lowering the film-breakup threshold.

ρ_p is the gas density under operating conditions (kg/m^3), calculated with allowance for the compressibility factor Z.

An increase in gas density (a pressure rise) leads to a decrease in the critical velocity (the denominator under the radical). This is explained by the fact that a denser gas possesses greater momentum and can strip the film at lower velocities.

Method for determining the minimum critical velocity $W_{min.cr}$

The minimum velocity $W_{min.cr}$, below which separation ceases due to insufficient centrifugal forces, is calculated in a similar manner but with a different structural transformation coefficient:

$$W_{min.cr.} = T_s \cdot \sqrt[4]{\frac{g \cdot \sigma_K}{\rho_p}}$$

where $T_{s\,min}$ = 3.0.

The velocity range between $W_{min.cr}$ and $W_{max.cr}$ represents the operating window of the apparatus. The ratio $W_{max.cr}$ / $W_{min.cr}$= 12/3 = 4 shows that the theoretical control range of a multicyclone with respect to flow rate is 1:4. In practice, however, this range is narrowed by flow maldistribution.

Experimental Verification

Computational methods require verification, as they do not account for the actual technical condition of the trays (fouling, corrosion, deformation). For this purpose, an instrumental diagnostic method is used, namely, isokinetic probing of the outlet stream.

Technology for measuring liquid droplet carry-over

Measurement of residual liquid content in gas (carry-over) is a complex metrological problem. Simple insertion of a sampling tube into the flow leads to substantial errors.

If the sample extraction velocity is lower than the flow velocity, gas streamlines bypass the sampler, whereas heavier liquid droplets enter it by inertia, resulting in an overestimation of concentration.

If the sampling velocity exceeds the flow velocity, gas is drawn from the periphery into the sampler while droplets pass by, leading to an underestimation of concentration.

To obtain reliable data, strict compliance with the isokinetic condition, where velocities are equal, is required. Specialized systems are used for this purpose.

SOP (Standard Operating Procedure) for isokinetic sampling

The proprietary work procedure at an operating facility is a sequence of stages, each ensuring the correctness and reproducibility of measurements. At the preparatory stage, the outlet pipeline geometry is analyzed to determine the optimal probe insertion point. The point is located on a straight section of the pipeline with an upstream straight length of at least ten pipe diameters and a downstream straight length of at least five pipe diameters. A lubricator, functioning as a lock chamber, is then installed on the sampling-point valve.

After completion of preparatory operations, the probe is introduced. The main valve is first opened to provide access to the flow. The probe is then mechanically inserted into the flow center at operating pressure. If necessary, scanning along the pipe diameter may be performed, enabling the construction of a flow-parameter distribution profile across the cross-section.

The next stage involves setting the measuring system's operating mode. Static pressure and differential pressure across the probe are measured. Simultaneously, the flow rate of the extracted sample through the instrument's microseparator is adjusted to equalize velocities and ensure the correctness of subsequent measurements. In this way, a stable regime is established in which sampling and parameter recording become representative of the entire flow.

Subsequently, direct data acquisition is carried out. The extracted sample undergoes separation: the liquid phase accumulates in a calibrated burette, while the gas phase passes through a high-precision flowmeter. The sampling time is recorded simultaneously, which is necessary for quantitative data processing. At the processing stage, the specific carry-over is calculated in mg/m^3, and an efficiency diagram is plotted. The proposed algorithm is shown in Fig. 3.

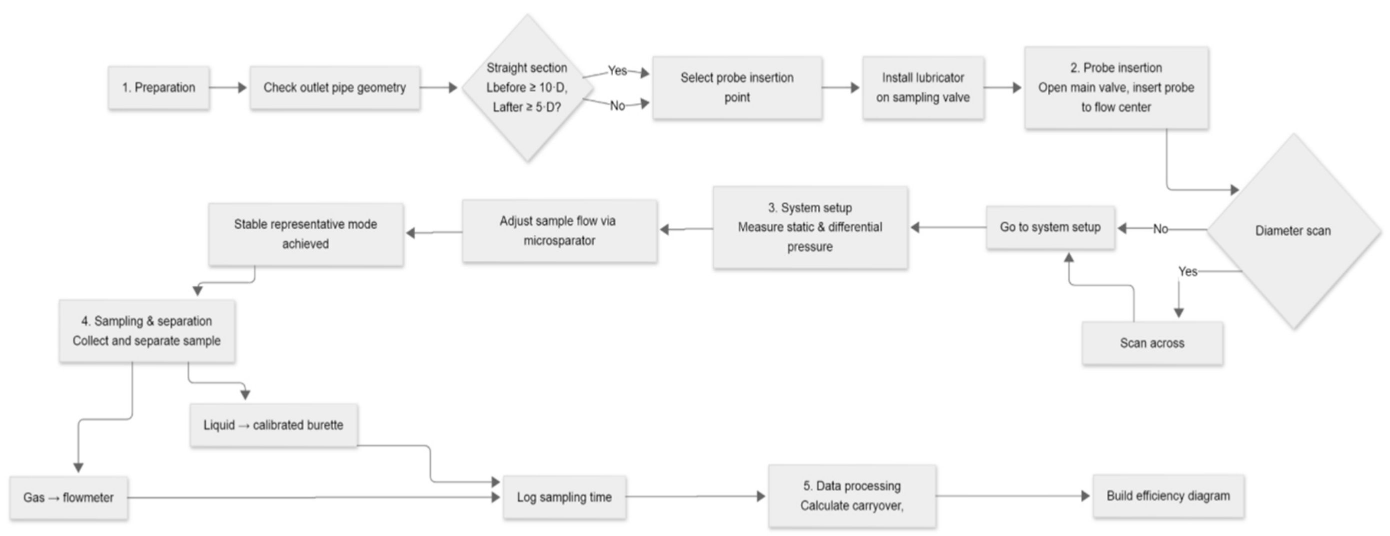

Fig. 3. Standardized In-Situ Flow Sampling Procedure

Based on measured liquid droplet carryover at various gas flow rates in the separation element, an experimental diagram of the apparatus's effective operating zone is constructed.

From the diagram shown in Fig. 4, the gas flow rate is determined at which the operating point lies in the middle of the effective operating zone at the vessel operating pressure.

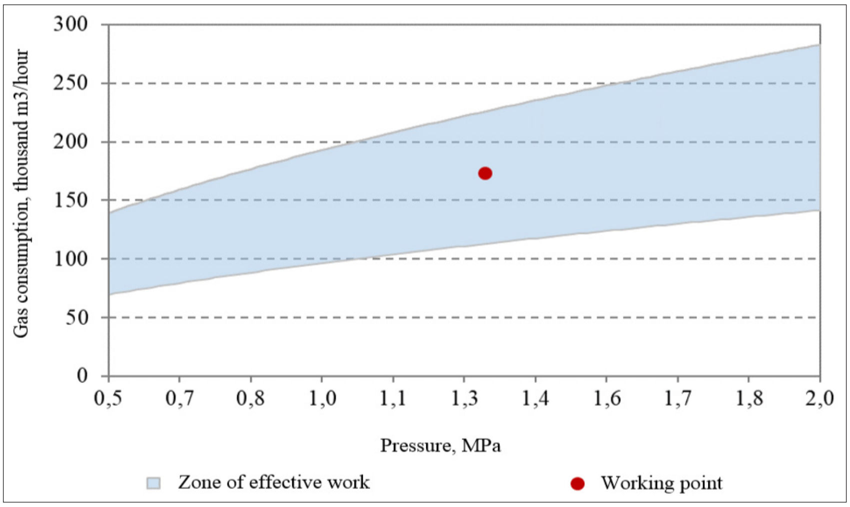

Fig. 4. Diagram of the effective operating zone of the device, obtained experimentally

Subsequent computations are performed by calculation.

CHAPTER 2. COMPUTATIONAL MODEL FOR OPTIMIZING ACTIVE AREA

Algorithm for Selecting the Optimal Regime

The central element of the methodology is the algorithmic determination of the system's target state. Knowing the boundaries W_{min} and W_{max}, a configuration must be chosen in which the average flow velocity is at the center of the stability range.

Consider the determination of the optimal velocity W_{opt}. The arithmetic mean of the critical velocities is adopted as the target parameter. This provdes the maximum safety margin against both potential further flow decline and short-term surges. The calculation is performed as follows:

$$W_{opt}(\pm 10\%) = \frac{W_{max.cr.} + W_{min.cr.}}{2}.$$

A ±10 % band is introduced so that, when determining the number of plugs (a discrete value), an integer number of elements can be selected as close as possible to the optimum.

At the same time, the physicochemical properties of the medium must be considered. A critical aspect is the accurate calculation of gas density. Application of the ideal gas law at pressures of 5–10 MPa yields errors of up to 20–30 %. An real gas equation of state must be used. The influence of temperature on surface tension is also considered. In a water–gas system, surface tension decreases only slightly with increasing temperature, whereas in a hydrocarbon condensate system, the decrease may be substantial, narrowing the operating range.

Calculation of Modernization Configuration

The process of converting nominal parameters into a modernization configuration consists of a series of steps.

Step 1: Conversion of flow rate to operating conditions. Input data are often given under standard conditions (Nm^3/day or million m^3/day). Conversion to the actual volumetric flow inside the vessel (m^3/s) is required:

$$q_c = \frac{Q_{nom} \cdot 10^6 \cdot P_n \cdot Z_p \cdot T_p}{86400 \cdot P_p \cdot Z_n \cdot n}$$

where:

Q_{nom} is gas capacity under standard conditions, million m^3/day;

P_n is atmospheric pressure, MPa;

P_p is operating pressure, MPa;

Z_n is compressibility factor at standard conditions;

Z_p is compressibility factor at operating conditions;

T_p is operating temperature.

Step 2: Calculation of required cross-sectional area (F_s). The required area of the separation elements F_s, m^2 is calculated as follows:

$$F_s = \frac{q_s}{W_{opt}}$$

Step 3: Determination of the number of elements (n_s). Given the geometric area of a single element: $f_s = 0{,}785 \cdot d_s^2$,

where d_s is the internal diameter of the separation element, the required number of active elements is

$$n_s = \frac{F_s}{f_s}.$$

The resulting value is rounded to an integer.

Case Study (Worked Example from Practice)

To demonstrate applicability of the methodology, a real example is considered of optimizing a first-stage separator at a West Siberian field.

In accordance with the proposed method, the required number of centrifugal elements to be plugged was calculated. The results are as follows:

Maximum critical gas velocity in the separation element $W_{max.cr.}$, m/s:

$$W_{max.cr.} = 12 \cdot \sqrt[4]{\frac{9{,}81 \cdot 0{,}07553}{5{,}472}} = 7{,}279 \text{ m/s}.$$

Minimum critical gas velocity in the separation element $W_{min.cr}$, m/s:

$$W_{min.cr.} = 3 \cdot \sqrt[4]{\frac{9{,}81 \cdot 0{,}07553}{5{,}472}} = 1{,}82 \text{ m/s}.$$

Optimal gas velocity in the centrifugal element W_{opt}, m/s:

$$W_{opt}(\pm 10\%) = \frac{7{,}279 + 1{,}82}{2} = 4{,}55 \text{ m/s}.$$

Nominal gas flow rate per second under operating conditions, m^3/s:

$$q_c = \frac{1{,}92 \cdot 10^6 \cdot 0{,}1013 \cdot 0{,}9825 \cdot 278{,}15}{86400 \cdot 0{,}66 \cdot 0{,}9981 \cdot 273{,}15} = 3{,}186 \text{ m}^3\text{/s}.$$

Required area of separation elements F_s, m^2:

$$F_s = \frac{4{,}55}{3{,}186} = 0{,}7 \text{ m}^2.$$

Cross-sectional area of a single element f_s, м^2:

$$f_s = 0{,}785 \cdot 0{,}1^2 = 0{,}00785 \text{ m}^2.$$

Number of separation elements n_s, units.:

$$n_s = \frac{0{,}7}{0{,}00785} = 89{,}2 \text{ units}.$$

In accordance with the proposed method, the required number of centrifugal elements to be plugged amounts to 89 units.

To simplify decision-making at the field, a software module (script) is proposed to replace manual calculations and nomograms. Fig. 5 shows a Python module for calculation.

```python
def calculate_plugs(P_p, T_p, Q_nom, N_total, d_c, sigma_k=0.075, Z=0.9):
    """
    Calculator for the required number of plugs (blocked elements) in a separator.

    Parameters:
    P_p     : Operating pressure, MPa
    T_p     : Operating temperature, K
    Q_nom   : Gas flow rate, million m³/day (standard conditions)
    N_total : Total number of elements
    d_c     : Element diameter, m
    sigma_k : Surface tension, N/m (default 0.075)
    Z       : Gas compressibility factor at operating conditions (default 0.9)
    """
    # 1. Gas density calculation (simplified using M = 16 g/mol for methane)
    R = 8.314          # Universal gas constant, J/(mol·K)
    M_gas = 16.04e-3   # Methane molar mass, kg/mol
    rho_p = (P_p * 1e6 * M_gas) / (Z * R * T_p)

    # 2. Critical velocities (for Ts = 12 and Ts = 3)
    g = 9.81
    term = (g * sigma_k / rho_p) ** 0.25
    W_max = 12.0 * term
    W_min = 3.0 * term
    W_opt = (W_max + W_min) / 2

    # 3. Convert flow rate to operating m³/s
    # P_n = 0.1013 MPa, T_n = 293.15 K, Z_n = 1.0
    P_n = 0.1013
    T_n = 293.15
    q_c = (Q_nom * 1e6 * P_n * Z * T_p) / (86400 * P_p * 1.0 * T_n)

    # 4. Element calculation
    f_c = 0.785 * d_c**2
    n_required = q_c / (W_opt * f_c)
    n_plugs = N_total - int(n_required)

    return {
        "W_opt": W_opt,
        "Active_Elements": int(n_required),
        "Plugs_Needed": n_plugs,
        "Efficiency_Zone": f"{W_min:.2f} - {W_max:.2f} m/s",
    }


# Example usage
result = calculate_plugs(P_p=5.0, T_p=278.15, Q_nom=1.92, N_total=181, d_c=0.10)
print(result)
```

Fig. 5. Python module for calculation

CHAPTER 3. PROCESS REGULATION AND MODERNIZATION TOPOLOGY

Design Solutions (Engineering Implementation)

Ensuring the tightness of plugged elements is a critical aspect of reliability. The use of improvised methods (such as wooden plugs and rags) is unacceptable. The methodology prescribes standardized mechanical plugs.

The design comprises several main components, whose functions are interrelated and aimed at ensuring the assembly's strength and tightness.

The support plate is a washer made of 09G2S carbon steel or 12Kh18N10T stainless steel. Its thickness is at least 3–4 mm, and geometric dimensions are selected such that the plate completely overlaps the cross-section of the element inlet nozzle and accommodates the mechanical loads arising during operation.

A tie rod in the form of a threaded stud of M10–M12 size extends along the entire length of the element and serves as the structural load-bearing link. To ensure tightness at the metal-metal contact, a paronite or fluoroplastic seal is placed between the contact points, forming a stable sealing line. The connection can be reliably secured using a nut with a spring (lock) washer, which prevents unthreading from vibration and other dynamic influences.

The installation principle is from below. The plug is mounted on the inlet end of the multicyclone (beneath the tray). This is a fundamentally important solution. The pressure drop across the tray (pressure below the tray is higher than above it) presses the plug against the element body, providing self-sealing. If the plug is installed from above (at the gas outlet), the pressure will tend to push it out. A plug for a centrifugal separator element with a mounting hole is shown in Fig. 6.

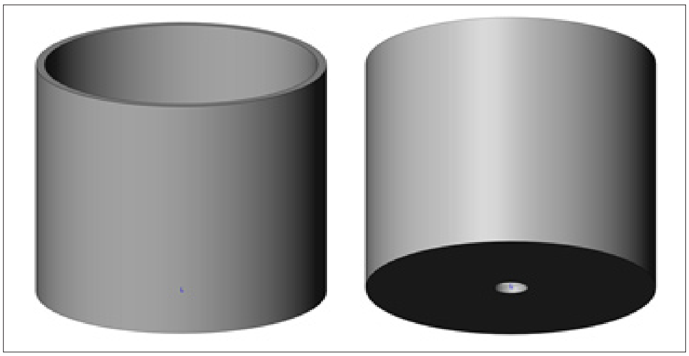

Fig. 6. Plug for a centrifugal separator element with mounting hole

Plugging Topology (Flow Distribution Rules)

The effectiveness of modernization depends not only on the number of plugs but also on their spatial arrangement. Improper distribution can create local turbulence zones and overloads.

Consider Scenario A: tangential gas inlet. With a side gas inlet to the vessel shell, a strong macro-vortex is formed. The centrifugal force of this vortex throws most of the gas and liquid toward the vessel wall. As a result, peripheral rows of multicyclones experience loads 1.5–2 times higher than the average, while the central part of the tray is underloaded.

Rule: To equalize the velocity profile, the peripheral rows (outer rings) must be plugged. This forces gas to move toward the tray center, loading previously underutilized elements and relieving the outer ones. Non-uniform loading of the central centrifugal aspects of the separation tray is shown in Fig. 7, and Fig. 8 illustrates plugging of the centrifugal elements in a separator with a tangential inlet.

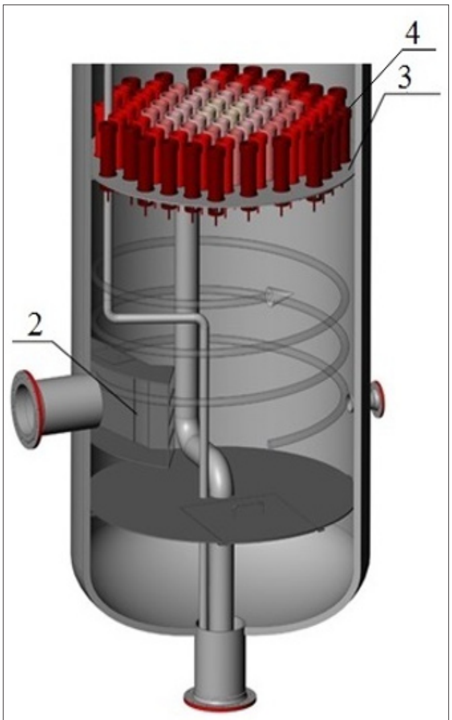

Fig. 7. Non-uniform loading of central centrifugal elements of the separation tray

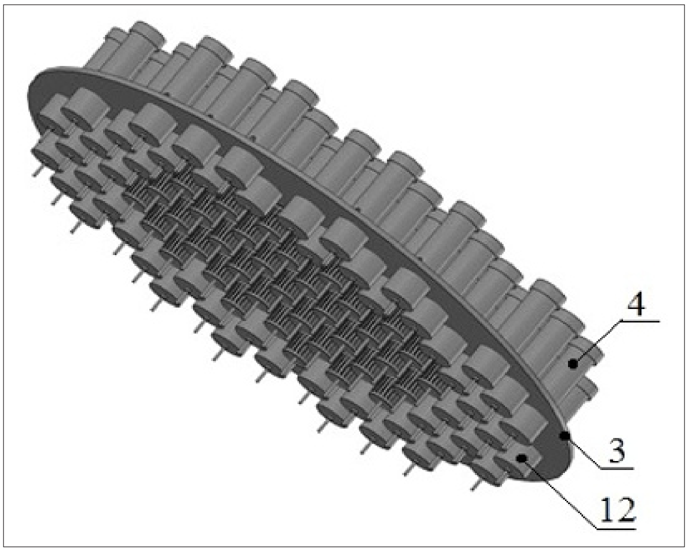

Fig. 8. Plugging of centrifugal elements for tangential inlet configuration

Consider Scenario B: radial inlet/mesh demister. If the vessel is equipped with a flow distributor that provides uniform feed, plugging the outer rows may create an artificial dead zone near the wall. Rule: Plugging is carried out in a checkerboard pattern or by uniform sectors to preserve the homogeneity of the aerodynamic field above the tray.

Work Procedure (Sequence of Operations)

HSE requirements must also be strictly adhered to, as all work is conducted on hydrocarbon processing systems in explosive zones.

During shutdown and preparation, the gas supply is shut off, and the inlet and outlet valves are shut. Pressure is then relieved to the flare, and blind flanges are installed on the pipelines as part of the lockout–tagout (LOTO) system, which excludes unauthorized start-up and medium access to the vessel.

Degassing and provision of safe entry into the vessel are then performed. To remove residual hydrocarbons, steaming is carried out, followed by sequential purging with nitrogen and air. After that, gas–air mixture analysis is performed, based on which a decision is made regarding the crew's admission to work in the confined space. Only upon confirmation of safe concentrations of hazardous and explosive components is personnel allowed to proceed to subsequent operations.

The plug installation stage includes a visual inspection of the tray and cleaning its elements of deposits, which is necessary for proper installation and reliable seating of components. Plugs are mounted in accordance with the approved layout (topology), defining their positions and configuration. After installation, the tightening torque of nuts is checked to ensure joint stability and eliminate the risk of depressurization during operation; photographic documentation is also performed as documentary confirmation of the correctness and completeness of the work performed.

At the assembly and start-up stage, vessel manholes are closed, mechanical blinds are removed, and nitrogen pressure testing is conducted to detect leaks. If the test is successful, gas feed is initiated, and the unit is brought to operating mode. To confirm the effectiveness of the method, control carry-over measurements are performed according to the procedure described in Section 1.3, enabling comparison of apparatus performance parameters before and after plug installation.

The key advantages of the method are reversibility, safety, and rapid implementation. Reversibility lies in the fact that, with increasing production or changes in operating regimes, plugs can be relatively easily dismantled without extensive installation work. Safety is ensured through the complete elimination of hot work, such as welding and cutting, thereby drastically reducing the risk of explosions and fires. Additionally, the method is characterized by high speed: the entire work package typically fits within one or two shifts, whereas a complete tray replacement can take weeks.

CONCLUSION

The completed study establishes a holistic, scientifically substantiated methodology for the adaptive renovation of vertical gas separators equipped with multicyclone trays under late-life production conditions, aimed at preserving the required gas-cleaning efficiency without capital expenditure or hot work. It is demonstrated that the key cause of the degradation of separation performance at the late stage of field development is associated not with the structural aging of the vessels as such, but with a fundamental misalignment between the gas-dynamic regime and the geometry of the actual active area of the tray as flow rate and pressure at the well pads decline. This misalignment drives the operating point beyond the effective inertial separation zone, leading to an avalanche-like increase in liquid-phase carryover and, consequently, intensifying corrosion–erosion impacts on pipelines and elevating the risk of catastrophic failures of compressor equipment.

From a scientific standpoint, the work concludes with the formulation and practical implementation of an efficiency triangle, whose vertices are velocity, pressure (through the gas–liquid mixture's density and rheology), and element design. Within this conceptual framework, the operability limits of a multicyclone element are represented via modified similarity correlations based on the Kutateladze criterion, which make it possible to determine the minimum and maximum critical velocities and , corresponding, respectively, to loss of film retention under insufficient centrifugal force and to the onset of intensive secondary entrainment upon film disruption under the action of shear stresses and wave instabilities at the phase interface. It is shown that the theoretical control range in terms of flow rate for a standard multicyclone element is on the order of 1:4; however, in fundamental apparatuses, it is further narrowed by maldistribution of flow among the components. The proposed criterion for selecting the optimal regime, by placing the operating point near the midpoint of the interval with a tolerance of ±10 %, simultaneously provides stability margins against both further flow-rate decline and short-term surges, while maintaining minimal carryover.

A fundamental feature of the methodology is its computational–experimental nature: a purely model-based approach is consistently coupled with instrumental diagnostics of the tray's actual technical condition. As a verification tool, a standardized isokinetic sampling procedure on the outlet gas pipeline is employed, which, under strict observance of the condition of velocity equality in the main flow and in the sampling line, makes it possible to obtain representative values of specific carryover in mg/m^3 and to construct experimental diagrams of the effective operating zone of the apparatus. Based on such diagrams, the actual position of the operating point under the current thermobaric conditions is determined, followed by transition to the computational stage: conversion of the nominal flow rate from standard conditions to the conditions inside the vessel, determination of the optimal velocity W_opt with allowance for the real gas density (from the real-gas equation of state) and surface tension, calculation of the required total cross-sectional area Fs of the active elements and of the number of operating multicyclones ns, with subsequent derivation of the number of components to be plugged. Implementation of the algorithm as a Python module eliminates the need for manual work with nomograms, reduces the risk of engineering errors, and makes the procedure accessible to routine operations personnel.

The engineering and process block of the methodology complements the theoretical constructs with specific design solutions that ensure tight, mechanically reliable isolation of part of the multicyclone elements, without interference with the vessel shell or the use of welding. A standardized design for mechanical plugs is described, incorporating a support washer, a through tie rod, and a sealing contour made of paronite or fluoroplastic, mounted from below at the inlet section of the element, which provides self-sealing due to the pressure differential across the tray. It is shown that the effectiveness of modernization is governed not only by the number of plugged channels but also by their topology: for tangential gas feed it is expedient to disable peripheral rows, redistributing the flow toward the tray center, whereas for uniform distribution (radial inlet, mesh demisters) a checkerboard or sectoral plugging pattern is required to maintain homogeneity of the aerodynamic field. The sequence of production operations, from lockout–tagout (LOTO) activities, degassing, and gas–air mixture analysis to plug installation, photographic documentation, and commissioning tests with control isokinetic sampling, ensures the reproducibility of the methodology and its conformity with industrial and explosion/fire safety requirements.

It is demonstrated that application of the developed approach to an industrial case of a first-stage separator in Western Siberia makes it possible, by isolating part of the multicyclone elements and bringing the average velocity in the operating channels to the optimal value, to return the operating point to the center of the effective zone, thereby restoring the regulatory carryover level (<5 mg/m^3), extending the service life of the equipment, and eliminating the need for costly separator replacement or factory-level retraying modernization. At the same time, the total cost of the intervention amounts to less than 1 % of the price of a new vessel, and all modifications are fully reversible: in the event of regime changes, commissioning of new wells, or reconfiguration of the field scheme, the plugs can be dismantled with minimal labor input. The totality of these results allows the conclusion that the proposed methodology for adaptive renovation of multicyclone separators constitutes a scientifically and metrologically verified tool for gas-dynamic optimization of the existing equipment fleet without CAPEX burden, addressed to engineering and technical personnel of production and processing enterprises, as well as to design and service organizations responsible for modernization of modular integrated gas-treatment units.

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