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Original Empirical Research

Regeneration of Filter Material of Hydrodynamic Vibration Filter

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Abstract

Introduction. In industrial filtration systems, one of the main challenges is reducing the filter capacity due to the accumulation of retained particles and the formation of sediment layer on the filter baffle. This results in increased hydraulic resistance, increased energy consumption, and forced service stops. Extending the lifespan of filter elements while maintaining productivity is a crucial technological challenge. This involves methods such as the regeneration of hydrodynamic filters, including the rotation of the filter element and the use of vibration effects. However, current research focuses on these methods individually, with no theoretical models for the combined effect of centrifugal and vibrational forces. Experimental data on the synergy between these forces has not been collected, and criteria for optimizing this combined effect have not been established considering operating parameters and the adhesive properties of sediment. The aim of this research was to develop a computational method for optimizing the combined centrifugal-vibration effect, based on an analytical and experimental study of its impact on the regeneration efficiency of hydrodynamic filters.

Materials and Methods. The research was conducted on a laboratory test bench with a hydrodynamic vibrating filter equipped with a cylindrical filter baffle made of a combined porous mesh metal (fineness of 10 µm), which could perform independent rotational and vibrational movements. To describe the condition for sediment particle detachment, an analytical model was developed based on the balance of forces acting on a particle on a rotating and vibrating surface. This allowed us to evaluate the effectiveness of filter regeneration based on operating parameters. The experiments were conducted using aqueous suspensions of electrocorundum (200–250 µm) and silicon carbide (60–80 µm) with a volume concentration of 0.1%. The regeneration mode involved a simultaneous increase in the rotational speed of the baffle to 1000 rpm and vibration with an amplitude of 1 mm at a variable frequency of 50, 60 and 70 Hz with the filtrate outlet closed to eliminate the change of pressure.

Results. Quantitative dependencies of the regeneration efficiency on rotational speed, vibration amplitude and frequency were experimentally determined. An analytical model of force balance was developed, which allowed predicting the degree of purification for any combination of these parameters. Verification of the model showed that the discrepancy between the calculated and experimental data did not exceed 15–20%, confirming its suitability for engineering calculations. Based on the model, a computational optimization method was proposed that provided a choice of a combination of operating parameters at which the required level of cleaning was achieved with minimal energy consumption and permissible mechanical loads on the structure.

Discussion. The low efficiency of purely centrifugal regeneration (2–20%) was explained by the fact that for fine particles, the ratio of adhesive forces to inertial forces was significantly higher than for coarse particles. This was consistent with the Derjaguin classical theory of adhesion. The synergistic effect of the combined effect was due to the addition of radial centrifugal force by tangential shear stresses generated by vibration, which ensured a more complete destruction of adhesive bonds in the sediment layer. The discrepancy between the model and the experiment in the range of 15–20% was mainly due to uncertainty in determining the adhesion characteristics of the particle –filter baffle pair. However, this level of accuracy was acceptable for the engineering selection of operating parameters. The obtained patterns were qualitatively consistent with the known literature data on the individual effects of rotation and vibration on sediment removal, but for the first time, they quantitatively describe their combined effect. One limitation of the study was the validation of the model for aqueous suspensions only, which required additional research to extend it to viscous and non-Newtonian media.

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Conclusion. It has been experimentally proven that the combination of centrifugal and vibrational effects can increase the regeneration efficiency of the hydrodynamic filter baffle by 60–80%, compared to 2–20% with rotation alone. An analytical model has been developed based on the balance of forces, and verified experimentally with an error of no more than 20%. This model is suitable for engineering calculations of optimal regeneration modes. It is demonstrated that the key parameter determining the accuracy of the forecast is the adhesion properties of particles, which require experimental determination for each system. The results provide a scientific basis for designing continuous self-cleaning filtration devices. A promising direction for future research is the adaptation of this technique to rheologically complex industrial environments, as well as optimizing energy consumption in the vibration system.

Keywords: filtration, regeneration, hydrodynamic filter, centrifugal cleaning, vibration cleaning

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Оригинальное эмпирическое исследование

Регенерация фильтровального материала гидродинамического фильтра

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Аннотация

Введение. В промышленных системах фильтрования одной из ключевых проблем является снижение пропускной способности фильтра вследствие накопления улавливаемых частиц и образования слоя осадка на фильтровальной перегородке. Это ведёт к росту гидравлического сопротивления, увеличению энергопотребления и вынужденным остановкам на обслуживание. Повышение ресурса фильтрующих элементов без потери производительности остаётся актуальной технологической задачей, для решения которой применяются методы регенерации гидродинамических фильтров — в частности, вращение фильтровального элемента и наложение вибрационных воздействий. Однако существующие исследования рассматривают эти методы преимущественно изолированно: отсутствуют теоретические модели, описывающие совместное действие центробежных и вибрационных сил, не получены экспериментальные данные о синергетическом эффекте их комбинирования, а также не разработаны критерии оптимизации такого комбинированного воздействия с учётом режимных параметров и адгезионных свойств осадка. Целью работы являлась разработка расчётного метода оптимизации комбинированного центробежно-вибрационного воздействия на основе аналитического и экспериментального исследования его влияния на эффективность регенерации гидродинамических фильтров.

Материалы и методы. Исследования проводились на экспериментальном стенде с гидродинамическим вибрационным фильтром, оснащённым цилиндрической фильтровальной перегородкой из комбинированного пористого сетчатого металла (тонкость очистки 10 мкм), которой независимо сообщались вращательное и вибрационное движения. Для описания условий отрыва частиц осадка была разработана аналитическая модель на основе баланса сил, действующих на частицу на вращающейся и вибрирующей поверхности. Она позволила оценить эффективность регенерации фильтра в зависимости от режимных параметров. Эксперименты проводились на водных суспензиях электрокорунда (200–250 мкм) и карбида кремния (60–80 мкм) объёмной концентрацией 0,1 %. Режим регенерации включал одновременное увеличение скорости вращения перегородки до 1000 об/мин и наложение вибрации с амплитудой 1 мм при варьируемой частоте 50, 60 и 70 Гц с перекрытием патрубка фильтрата для устранения удерживающего перепада давления.

Результаты исследования. Экспериментально установлены количественные зависимости эффективности регенерации от частоты вращения, амплитуды и частоты вибрации. Разработана аналитическая модель баланса сил, позволяющая прогнозировать степень очистки для произвольных сочетаний указанных параметров. Верификация модели показала, что расхождение расчётных и экспериментальных данных не превышает 15–20 %, что подтверждает её пригодность для инженерных расчётов. На базе модели предложен расчётный метод оптимизации, обеспечивающий выбор комбинации режимных параметров, при которой достигается требуемый уровень очистки при минимальных энергозатратах и допустимых механических нагрузках на конструкцию.

Обсуждение. Низкая эффективность чисто центробежной регенерации (2–20 %) объясняется тем, что для мелкодисперсных частиц отношение адгезионных сил к инерционным существенно выше, чем для крупных, что согласуется с классической теорией адгезии Дерягина. Синергетический эффект комбинированного воздействия обусловлен дополнением радиального центробежного усилия тангенциальными сдвиговыми напряжениями, генерируемыми вибрацией, что обеспечивает более полное разрушение адгезионных связей в слое осадка. Расхождение модели с экспериментом в пределах 15–20 % связано главным образом с неопределённостью в определении адгезионных характеристик пары «частица – фильтровальная перегородка», однако такая точность является приемлемой для инженерного подбора режимных параметров. Полученные закономерности качественно согласуются с известными литературными данными о раздельном влиянии вращения и вибрации на удаление осадков, но впервые количественно описывают их совместное действие. Ограничением работы является валидация модели только для водных суспензий, что требует дополнительных исследований при переходе к вязким и неньютоновским средам.

Заключение. Экспериментально доказано, что комбинирование центробежного и вибрационного воздействий позволяет повысить эффективность регенерации фильтровальной перегородки гидродинамического фильтра до 60–80 % по сравнению с 2–20 % при использовании только вращения. Разработана аналитическая модель на основе баланса сил, верифицированная экспериментально с погрешностью не более 20 %, пригодная для инженерного расчёта оптимальных режимов регенерации. Показано, что ключевым параметром, определяющим точность прогноза, являются адгезионные свойства частиц, требующие экспериментального определения для каждой конкретной системы. Результаты создают научную основу для проектирования самоочищающихся фильтровальных аппаратов непрерывного действия. Перспективным направлением является адаптация предложенной методики для реологически сложных промышленных сред и оптимизация энергопотребления вибросистемы.

Ключевые слова: фильтрование, регенерация, гидродинамический фильтр, центробежная очистка, вибрационная очистка

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Introduction. Purification of process fluids and wastewater [1] from mechanical impurities by filtration is a mandatory and essential process in industries such as petroleum chemistry, energy, and water treatment [2]. The effectiveness of this process directly determines the stability of technological cycles, the service life of equipment, the quality of final products, and the compliance with environmental regulations [3]. The main operational challenge in this field is the intense pollution of the filter media (filter baffle) during operation. This leads to a sharp increase in hydraulic resistance, which, in turn, causes a significant increase in energy consumption [4]. In addition, the active overgrowth of the baffle with sediment increases the risk of mechanical failure and leads to unplanned production stops for regeneration or replacement of filter elements. Traditional cleaning methods, such as backwashing, require shutting down the filter or using complex systems with duplicate lines, which reduces overall productivity and increases capital costs [5].

The use of filters with the possibility of continuous or periodic regeneration without stopping the main process is considered as a promising solution to this issue. One such type of device is the hydrodynamic filter (HDF), which combines the effects of centrifugal separation and tangential flow along its surface to reduce the deposition of particles on the filter baffle [6]. Unlike filtration centrifuges, in the HDF, the flow is directed from the outside into the rotating FB, enhancing the effect of centrifugal forces on the formed sediment layer [7]. Another approach to intensifying filter regeneration is the use of vibration on the filter element, which helps to break down adhesive bonds in the sediment layer [8].

An analysis of modern research shows that the effects of FB rotation [7] and vibration [8] on the filtration process have been studied, as a rule, in isolation. At the same time, there are practically no systematic studies in the scientific literature on the combined effect of these two types of force fields on the effectiveness of hydrodynamic filter regeneration. Additionally, there are no universal calculation methods to quantify the efficiency of this combined effect, which takes into account key factors, primarily the adhesive properties of the trapped particles in relation to the filter baffle material [9]. Thus, there is an obvious scientific and practical gap due to the lack of a methodology for the reasonable selection of optimal modes of joint centrifugal and vibrational action based on the physical model of the particle separation process.

The aim of this research is to conduct an experimental and analytical study of the synergistic effect of combining centrifugal and vibrational forces on the regeneration process of a hydrodynamic filter's baffle, and to develop a verified calculation method for optimizing regeneration parameters based on the results.

In order to achieve this goal, several sequential tasks have been formulated:

– analysis of literature data on FB regeneration methods and identification of a gap related to the complex effects of force fields;

– development of analytical and computational models of the process of particle separation from the FB based on the balance of retaining (adhesion forces, flow pressure force) and tearing (centrifugal force, inertial force from vibration) forces;

– experimental research on a specially designed test bench of the separate and combined effects of the FB rotational velocity, as well as the amplitude and frequency of vibration on the efficiency of sediment removal during filtration of suspensions with particles of various nature (electrocorundum, silicon carbide);

– verification of the developed computational model by comparing analytical estimates of regeneration efficiency with the experimental data obtained.

Materials and Methods. The research was conducted on a specially designed bench with a hydrodynamic vibration filter. Figure 1 presents its diagram.

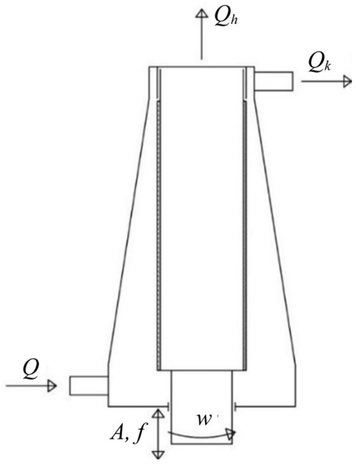

Fig. 1. Diagram of a hydrodynamic vibrating filter (*Q* — flow rate of the initial liquid, Q_h — flow rate of the purified liquid, *Qk* — flow rate of the concentrate, *w* — rotation speed of the filter baffle, *A* — amplitude of vibration, *f* — frequency of vibration

The main design feature of the device was the possibility of independent transmission to the cylindrical filter baffle of rotational motion from the electric motor and reciprocating (vibratory) motion from the vibration stand. The main geometric parameters were: height of the case — 186 mm, outer diameter of the case — 21 mm, and thickness of the case — 1 mm. A more detailed description of the principle of operation and layout is given in [10].

To analyze the regeneration process, a model based on the balance of forces acting on a particle in a sediment layer on a vibrating and rotating surface was used (Fig. 2), by analogy with the approaches described in the works “Features of the Regeneration Process of the Filter” [11] and “Slotted Filter Regeneration Efficiency” [12].

The separation condition of a particle could be described by the inequality:

$$cos(\varphi)\left(\left(mg+F_{wv}\right)^2+\left(F_{wc}\right)^2\right)>\left(F_t\right)^2+\left(F_n+F_{\Delta P}\right)^2. \quad (1)$$

Having divided both parts by $(mg)^2$, which characterized the total weight of sediment on the filter baffle, we obtained the expression for regeneration efficiency:

$$\eta<\left[\frac{\left(mg+F_{wv}\right)^2+\left(F_{wc}\right)^2}{\left(gm\right)^2}-\frac{\left(F_t\right)^2+\left(F_n+F_{\Delta P}\right)^2}{\left(gm\right)^2}\right]^{0,5}, \quad (2)$$

where η characterized the regeneration efficiency. If η = 1, all particles were removed from the filter media during regeneration.

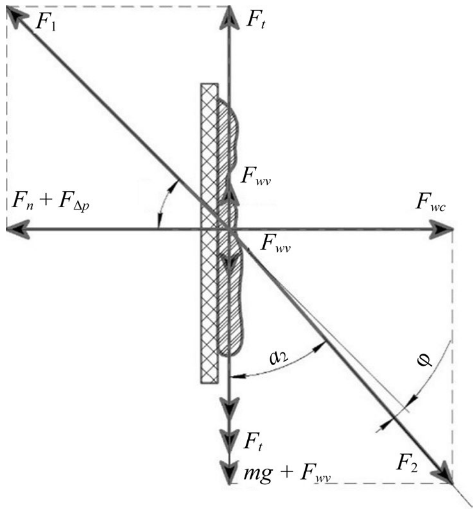

Fig. 2. Diagram of the action of forces, where mg, Newton (hereinafter referred to as n) — weight of the sediment layer (*m* — mass, kg; g — acceleration of gravity m/s^2); F_n, *H* and F_t, n — normal and tangential components of the adhesion force, F_{wv}, *n* and F_{wc}, n — forces arising during regeneration due to vibration and rotation of the filter baffle, respectively, $F_{\Delta p}$, *n* — pressure drop force on the baffle

Forces F_{wc} and F_{wv} depended on the mode of the operation of the device, rotation speed and vibration parameters [13], and were calculated using the formulas:

$$F_{wc} = mr\left(\frac{2\pi v}{60}\right)^2, \tag{3}$$

$$F_{wv} = mA\left(2\pi f\right)^2, \tag{4}$$

where r — radius of the filter baffle, m; v — filter baffle rotation speed, rpm; A — vibration amplitude, m; f — vibration frequency, Hz [14].

The force of the pressure drop, according to the theory of filtration with the formation of incompressible sediment, would be equal to [15]:

$$F_{\Delta p} = \Delta PS, \tag{5}$$

where ΔP — pressure drop on the baffle, Pa; S – area of the filter baffle, m^2. The pressure drop during operation and sediment accumulation would increase [16].

According to Deryagin's theory, the force of normal separation was expressed by the formula:

$$F_n = 4\pi\sigma r, \tag{6}$$

$$F_t = \mu F_n, \tag{7}$$

where σ — surface tension at the boundaries of two bodies; r — curvature radius of the particles, μ — friction coefficient.

Two types of particles were used as mechanical impurities (dispersed medium): electrocorundum and silicon carbide. Water was used as a purifying medium (dispersion medium). The characteristics of the particles are presented in Table 1.

Table 1

Characteristics of contaminant particles

Particle type	Particle layer permeability coefficient, m^2	Density, kg/m^3	Particle diameter, μm
Electrocorundum	$3.2 \cdot 10^{-14}$	3950	200–250
Silicon carbide	$4.2 \cdot 10^{-14}$	3200	60–80

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A permeable material, made using the technology developed at Bauman Moscow State Technical University, hot-rolling in vacuum based on metal meshes with a cleaning fineness of 10 µm, the so-called combined porous mesh metals, was used as a filter baffle [17]. The characteristics of the filter baffle were determined in accordance with [18]. The permeability of the baffle and sediment layer [19] was determined experimentally directly on the machine under study. Water at room temperature was used as the dispersion medium. A suspension with a volume concentration of 0.1% was prepared in a 300 liter container equipped with a paddle mixer to maintain uniformity of the composition.

The experiment was conducted as follows.

1. Preparation of the suspension. A homogeneous aqueous suspension with a mass concentration of solid particles (contaminants) of 0.1% by volume was prepared in a tank equipped with an electric mixer.

2. Filtration cycle (operating mode). The suspension was fed to the filter inlet. The filter baffle rotated at a constant speed of 300 rpm. The filtration process lasted for a predetermined length of time or until a specific pressure drop was achieved.

3. Initiation of the regeneration mode. At the end of the filtration time, a 30-second regeneration stage began, which included:

– closing the outlet pipe of the purified filtrate to eliminate the holding force caused by the pressure drop;

– simultaneous increase of the rotation speed of the filter baffle to 1000 rpm;

– simultaneous activation of the vibration effect on the baffle with an amplitude of 1 mm. At the same time, the vibration frequency varied from experiment to experiment, taking values of 50, 60 or 70 Hz.

4. Removal of the regenerated sediment. During the entire regeneration stage, the liquid was directed into the concentrate outlet, thereby entraining the particles separated from the baffle.

5. Return to the operating mode. After 30 seconds, the regeneration mode was turned off: the vibration stopped, the rotation speed of the partition decreased to 300 rpm, and the filtrate nozzle opened. The machine returned to step 2 for the next filtration cycle.

A Dwyer MFS-11 magnetic induction flowmeter with a relative measurement error of ± 2% manufactured in the USA was used to measure the flow. To measure the differential pressure, Hyadac HDA 4748—H-0009-000 pressure sensors (reduced error ± 0.5%) manufactured in Germany with the HMG 3000 data logger were used. Concentration control was performed using FCU 2000 and CS 2000 analyzers or a Photon-965 photonephelometer (Russia). An asynchronous electric motor (Russia) and a Tira Vib vibration stand (Germany) were used as the drive.

Results. Figure 3 demonstrates the results of computational and experimental studies on the efficiency of filter material regeneration during the purification of liquid from electrocorundum.

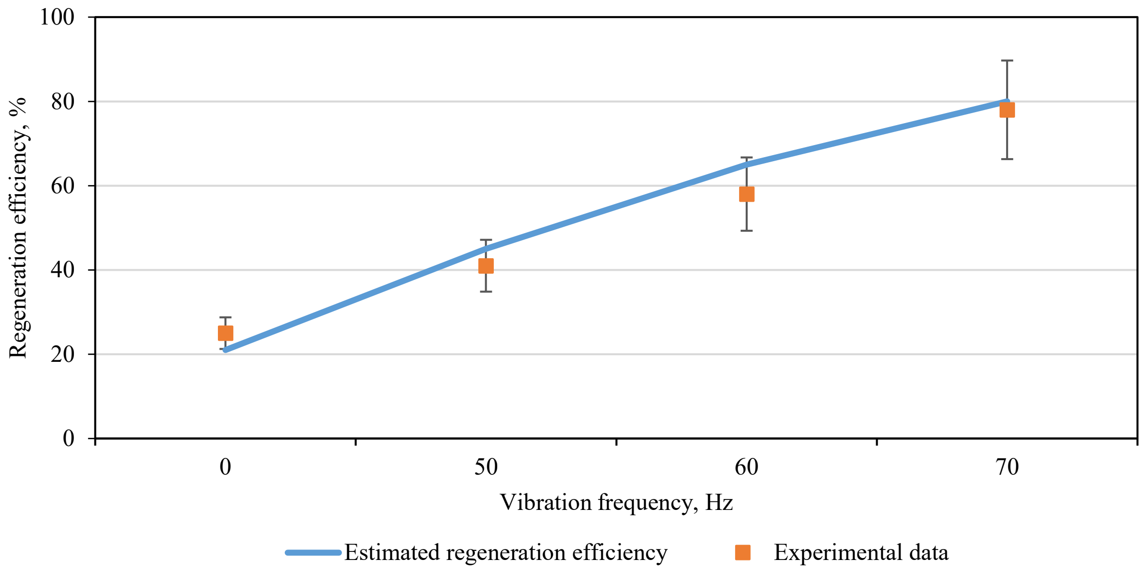

Fig. 3. Experimental and calculated data on the regeneration of the filter baffle after a cycle of filtration of liquid from electrocorundum

The results of computational and experimental studies on the efficiency of filter material regeneration during the purification of liquid from silicon carbide are presented in Figure 4.

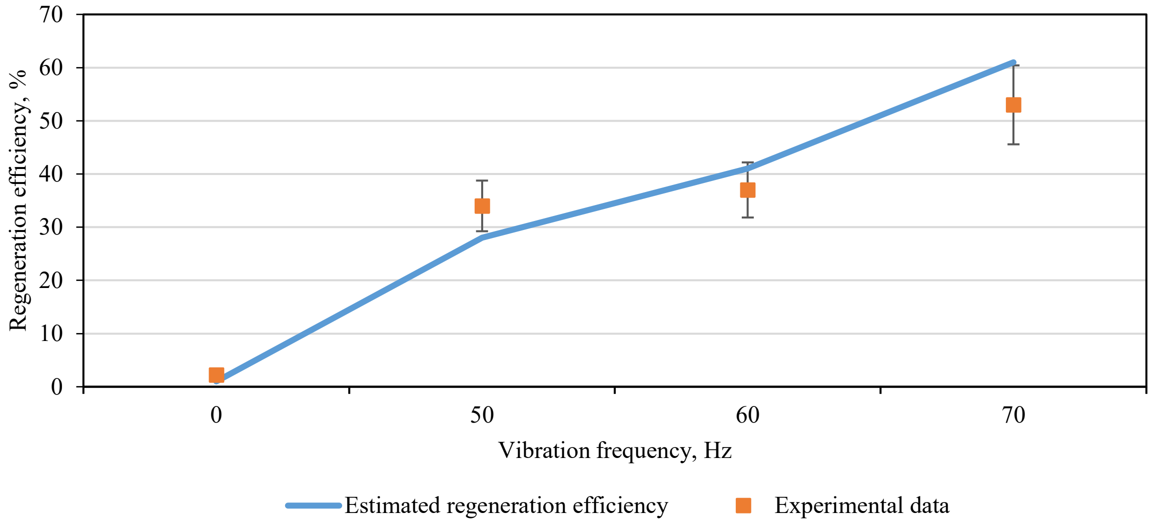

Fig. 4. Experimental and calculated data on the regeneration of the filter baffle after performing a cycle of liquid filtration from silicon carbide

The results of the experimental efficiency of regeneration (η) performed for two types of contaminants, coarse-grained electrocorundum and fine-grained silicon carbide, presented in Figures 3 and 4. They show the following:

– the use of only centrifugal action (pulsed acceleration of FB to 1000 rpm) showed low efficiency: for electrocorundum, n ≈ 20%, and for silicon carbide— only about 2%;

– the combination of centrifugal action with vibration (amplitude 1 mm, frequency 70 Hz) led to a synergistic effect. The regeneration efficiency for electrocorundum increased to 80%, and for silicon carbide — up to 60%.

Figures 3 and 4 also show the calculated curves obtained using the developed force balance model (1). A satisfactory qualitative and quantitative correspondence between the model and the experimental points was observed for both electrocorundum and silicon carbide. The maximum discrepancy between the calculated and experimental values of the regeneration efficiency did not exceed 15–20%, which was an acceptable level of accuracy for engineering calculations of the process dynamics.

Discussion. The results obtained allowed us to analyze the physical mechanisms behind the regeneration process and evaluate the limits of the applicability of the developed model.

1. Analysis of the effectiveness of various regeneration modes. A significant difference in the efficiency of centrifugal action for electrocorundum (20%) and silicon carbide (2%) was fully consistent with the theory of adhesion. For smaller particles of silicon carbide (60–80 µm), the ratio of adhesive forces to the mass of the particle (and therefore to inertial forces) was significantly higher than for large particles of electrocorundum (200–250 µm). Thus, centrifugal force alone was not sufficient to overcome the adhesive bonds of fine sediment.

2. Synergetic effect nature. Achieving an efficiency of 60–80% with combined exposure confirmed the hypothesis of different and mutually complementary mechanisms of layer destruction. Centrifugal force created a predominantly radial tearing force. Vibration, in turn, induced tangential shear stresses in the sediment thickness and reduced the friction force between the particles and the FB surface due to micro-displacements. The combined effect of these factors ensured a more complete destruction of adhesive bonds.

3. Verification of the calculation model. The discrepancy between the calculated and experimental data in the range of 15–20% indicated the adequacy of the proposed approach based on the power balance. The main source of the error was probably related to the difficulty in accurately determining the adhesive forces (Fn, Ft) for a specific “particle material — FB material” pair. The achieved accuracy was satisfactory for engineering calculations, which were not intended for an absolute forecast, but rather a comparative analysis of modes and selection of optimal parameters.

4. Practical significance and limitations. The results showed that the combined method increased the BF life compared to the use of the centrifugal force alone. The main practical limitation was the need to experimentally determine the adhesive characteristics of new types of contaminants, as their theoretical calculation involved significant uncertainty. In addition, the model was validated for aqueous suspensions. Its application to viscous or non-Newtonian liquids required further research, taking into account changes in hydrodynamic and adhesive conditions.

Conclusion. In the course of the research, we achieved the goal: the effectiveness of the combined centrifugal-vibration method for regenerating the filter baffle of a hydrodynamic filter was experimentally and theoretically substantiated. The following main conclusions were formulated:

1. It was established that the separate application of centrifugal action (rotation speed up to 1000 rpm) was characterized by low regeneration efficiency (2–20%), especially for fine particles with high specific adhesion.

2. The increasing effect of combining BF rotation with vibration action (amplitude 1 mm, frequency 70 Hz) was proven, which made it possible to increase the regeneration efficiency by up to 60% for silicon carbide and up to 80% for electrocorundum.

3. Computational model based on the balance of holding and tearing forces was developed and experimentally verified. The model made it possible to predict the efficiency of regeneration with an accuracy acceptable for engineering practice (error <20%) and select optimal parameters (rotation speed, frequency and amplitude of vibration) depending on the dispersed composition and nature of pollutants.

4. It was crucial for the accuracy of the model to consider the adhesive properties of particles, as they determined the need for experimental determination in specific filtration conditions.

Promising areas for further research include the adaptation of the technique to rheologically complex media, such as petroleum products and pulps, as well as the minimization of energy consumption of the vibration excitation system. Additional tests of the developed hydrodynamic vibration filter [20] are planned to be conducted in conditions simulating real industrial processes. The results obtained form the basis for the development of highly efficient filtration systems for the chemical, petrochemical, and water treatment industries.

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