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Computer modelling of the flow structure in a combined mixer for aqueous suspensions with solid and gas phases

Computer modeling of multiphase flows in mixers for aqueous suspensions with solid and gas phases opens up new opportunities for optimizing mixing processes in industry. The creation of CFD-DEM models allows taking into account the interaction of liquid, solid and gas phases, fixing the features of circulation, mass transfer and rheological behavior of the medium. The article considers the features of the formation of the flow structure in a combined-type mixing chamber, analyzes the nature of changes in turbulent and convective processes in the presence of a gas phase and solid inclusions, and also substantiates approaches to building effective mixing modes.

Keywords: CFD-DEM modeling, multiphase flows, combined mixer, mass transfer, gas bubbles, circulation structures.

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Introduction

Computer modeling of flow structures in mixers for aqueous suspensions containing solid and gas phases remains one of the priority areas of applied hydrodynamics and mechanical engineering.

The formation of an optimal multiphase flow structure directly determines the energy efficiency of mixing processes, the quality of the final product, and the resource load on the equipment.

The issue of improving the efficiency of mixing systems is highly relevant in the fields of water treatment, chemical technology, and mineral processing, where liquid-solid-gas media with complex rheological behavior dominate [1].

Analytical approaches based on simplified flow models do not fully capture the dynamics of multiphase systems.

Computational fluid dynamics (CFD) and discrete element modeling (DEM) methods offer opportunities for analyzing local flow characteristics, phase interactions, mixing regimes, and the development of boundary structures [2].

Computer modeling enables consideration of the multifactorial nature of processes in which mechanical, hydrodynamic, and thermal effects are realized simultaneously.

Analysis of Recent Research and Publications

The problem of numerical modeling of multiphase flows in mixing systems has evolved gradually, as the challenges of applied hydrodynamics became more complex.

O. Kasat, A.R. Khopkar, V.V. Ranade, and A.B. Pandit [1] laid the foundation for describing the processes of solid phase mixing in liquid media, using computational fluid dynamics (CFD) combined with discrete element modeling (DEM).

Their calculations made it possible to identify patterns of solid inclusion transport in mechanical mixers and to formulate criteria for evaluating mixing efficiency.

The challenges of modeling dense multiparticle flows were systematized by S. Van and Y. Shen [2], who emphasized the complexity of describing multiphase interactions in conditions of high discrete element concentration.

Their approaches aim to expand the capabilities of CFD-DEM modeling by integrating multiphysical models of mass transfer, heat transfer, and chemical reactions.

Local aspects of mixing processes were examined by S. Duan, S. Feng, C. Peng, C. Yang, and Z. Mao [3], who analyzed the micro-level structure of mixing in gas-liquid and solid-liquid media.

Their application of the CFD-E approach made it possible to trace the relationship between local concentration fluctuations and the macroscopic efficiency of mass transfer.

A.M. Zapata Rivera and his colleagues [4] demonstrated that without considering empirical observations, it is impossible to achieve a high correlation between simulation results and real three-dimensional flows in mixing tanks.

Understanding the spatial variability of multiphase medium properties was advanced by V.S. Biletskyi [5], who emphasized the need to adapt numerical algorithms to changes in phase density and viscosity during flow.

Based on his findings, a new concept for constructing CFD models for complex technological systems has been formulated.

In discussions about transitions between different flow regimes, D.A. Alaita [6] made a notable contribution by highlighting the critical importance of accounting for laminar-to-turbulent transitions in particle-laden flows.

His approach established new requirements for models aiming to accurately reproduce regime dynamics under real-world conditions.

High-speed multiphase processes were explored by D. Friso [8], who demonstrated how the structure of momentum and heat transfer changes with increasing Reynolds number.

V.M.S. Vullenweber and his colleagues [9], studying the micro-level behavior of solid particles in turbulent flows, showed that particles not only passively move with the flow but also actively influence its local characteristics, altering the structure of turbulent fluctuations.

The combination of approaches proposed by the aforementioned researchers indicates that numerical modeling of multiphase flows is entering a new stage of multiphysical integration.

The description of phase interactions, consideration of changing rheological properties, and the incorporation of turbulent effects are increasingly being combined within unified computational models, opening new prospects for solving complex engineering challenges.

Identification of Previously Unresolved Aspects of the General Problem

In recent years, computer modeling of multiphase flows has made significant progress; however, certain aspects related to mixing systems with complex configurations remain insufficiently studied.

Most existing models focus on describing two-phase media, which creates difficulties in accurately reproducing real processes involving the presence of a gas phase [2; 4].

The presence of gas alters circulation contours, modifies local velocity fields, and affects mass transfer efficiency, thus requiring more sophisticated numerical analysis approaches and a transition to three-phase models.

In studies dedicated to CFD-DEM modeling, the issue of accounting for turbulent effects during the interaction of discrete solid particles with liquid and gas phases remains relevant [3; 9].

Simplifications in modeling these processes limit the ability to accurately describe real mixing phenomena, where flow fluctuations and micro-level interactions significantly influence suspension stability and mass transfer efficiency.

The lack of consideration of these features complicates the application of numerical models in practical tasks where high accuracy in reproducing multiphase dynamics is required.

Finally, for combined-type mixers, where local high-velocity flows, recirculation zones, and phase segregation coexist, there are no universal numerical models capable of capturing both the macro- and micro-level flow structures during interactions between all phases [1; 5].

Thus, the scientific task lies in developing a comprehensive CFD-DEM model of the flow structure in a combined mixer for aqueous suspensions containing solid and gas phases, taking into account the effects of turbulence, interphase interactions, and multiphase instability.

Problem Statement

The aim of this article is to develop a conceptual CFD-DEM model of the flow structure in a combined mixer for aqueous suspensions containing solid and gas phases.

In line with this objective, the research focuses on identifying the patterns of hydrodynamic structure formation in a multiphase environment, analyzing the influence of the mixer's geometric parameters on the dynamics of phase interactions, and substantiating criteria for optimizing the mixing process.

Achieving this goal involves the application of computer modelling using computational fluid dynamics (CFD) methods to describe the flow of the liquid and gas phases, discrete element modelling (DEM) to simulate the dynamics of solid particles within the multiphase flow, as well as a multiphysics approach to integrate models of turbulence, mass transfer, and phase interactions.

Main Material and Results

The flow of the medium in combined mixers is not formed as a simple phase combination, but as a complex interaction process, where the liquid, solid, and gas components simultaneously contribute to the construction of a dynamic, changing system.

The mutual penetration of phases creates a dynamic structure in which local circulations, convective transfers, and turbulent fluctuations continuously influence each other, leaving no space for the establishment of stable regimes.

The formation of the flow is accompanied by constant changes in velocity, density, and viscosity in different areas of the mixer, leading to the appearance of temporary zones of order or, conversely, local disruptions of circulation loops.

Each disturbance in the flow initiates a wave of subsequent changes that alter the overall picture even at the macrostructural level.

This dynamic nature makes it impossible to describe the process through fixed instantaneous states and requires an approach that accounts for the continuous temporal evolution of the environment.

In complex mixing systems, no characteristic—whether velocity, concentration, or flow structure—remains constant, but instead continuously evolves in a chain of self-transformation, which defines the primary challenges in numerical modelling of multiphase flows.

The geometry of the mixer determines the architecture of the flow at a fundamental level. A cylindrical chamber with a rotor of combined blade shape installed at the center creates conditions for the development of two main types of motion: axial lifting of the mixture due to the mechanical rotation of the rotor and secondary circulatory currents resulting from the injection of gas through nozzles (Fig. 1).

The interaction of these two mechanisms defines the primary nature of the multiphase environment, where solid particles do not merely follow the flow but constantly alter their trajectories in response to local changes in velocity, pressure, and turbulent stresses.

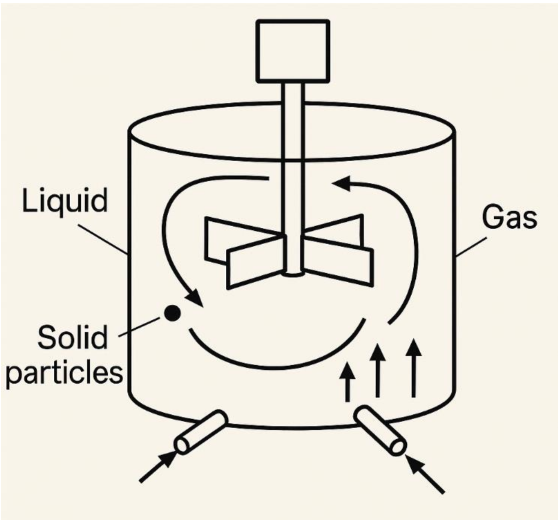

Figure 1 – Schematic of a combined mixer for aqueous suspensions with solid and gas phases

At approximately half the height of the mixing chamber, the zone of most intensive mixing forms. In this area, turbulent energy reaches its highest levels, which ensures active mass transfer between the liquid phase, gas bubbles, and solid inclusions [8]. The upper layers of the chamber and the regions near its bottom are characterized by a reduced level of turbulent fluctuations, where the accumulation of solid particles and gas bubbles occurs, creating the risk of forming zones with reduced mass transfer.

The dynamics of these processes depend not only on the structural parameters of the mixer but also on the operating characteristics of the system – rotor speed, gas flow intensity, liquid phase viscosity, and solid component concentration (Fig. 2). It is the complex interaction of these factors that determines the possibility of maintaining a homogeneous flow state over time.

The stratification of the medium, revealed during the simulation, is not a random phenomenon. It reflects the natural balance of forces in the mixing system: mechanical activation, gravitational settling, and the buoyant force of gas bubbles. An increase in the concentration of the solid phase in the peripheral zones of the chamber indicates insufficient efficiency of local convective mechanisms.

The discovery of the spiral logic of particle movement allows for a better understanding of not only the mechanisms of their movement but also the nature of the formation of zones of active and passive mass exchange.

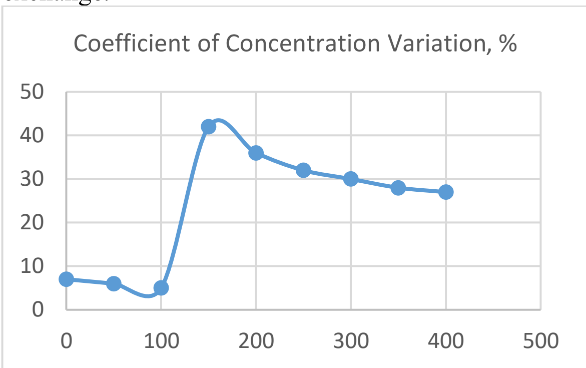

Figure 2 – Dependence of the solid phase concentration variation coefficient on rotor speed

Computer modelling of discrete trajectories shows that solid particles move from the central axis to the periphery and return back through the formed recirculating flows (Fig. 3). The delay of particles in stagnant zones near the walls is related to the combination of turbulent dispersion, gravitational settling, and local velocity gradients [3; 9].

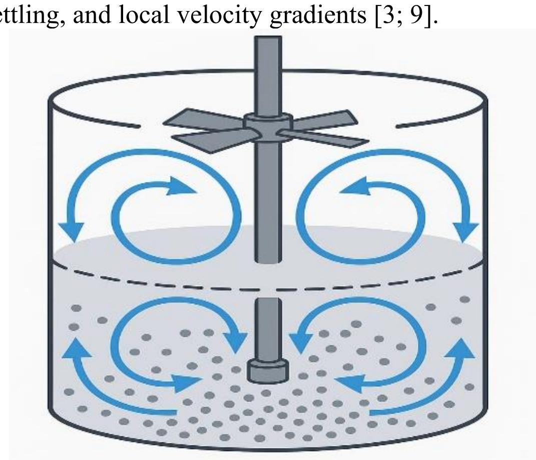

Figure 3 – Circulation contours and particle trajectory movement in the mixer.

In a multiphase environment of a combined mixer, no process exists in isolation: energy transfer between different scales, phase interactions, and continuous fluctuations in structure form a complex network of changes, where the state of one element directly influences the behavior of the entire flow. Disturbances in local flow, changes in concentration or velocity in a particular zone, immediately affect other levels, creating a dynamic system of interdependent reactions that constantly evolve over time.

The integration of the gas phase into the overall flow structure changes not only the local parameters but also the principle of organizing the circulation processes. When gas bubbles are introduced through nozzles at the lower part of the mixing chamber, they create lifting forces that alter the direction of primary convective flows and simultaneously restructure the internal flow structure. The formation of vertical circulation contours based on gas bubbles increases mass transfer intensity and prevents the formation of horizontal layers with increased solid-phase concentration, which often occur in systems without aeration.

The distribution of gas bubbles in the chamber shows stratification by size, adding another level of complexity to the dynamics of the environment. Larger bubbles concentrate near the axis, where the axial flow has the highest velocity, while smaller bubbles more evenly spread across the radius, forming a network of micro-flows. These small-scale structures enhance the exchange of substances between phases and ensure the expansion of the spatial region of effective interaction, maintaining the system's dynamic activity even in regimes with reduced primary flow intensity.

Such a multi-level distribution of the gas phase changes the overall structure of circulation: where small bubbles dominate, there is higher mixing efficiency due to the increased interfacial surface area. The enhanced mass transfer mechanism is realized through small bubbles, which cannot be achieved by mechanical mixing alone.

The turbulent flow structure, formed by the simultaneous influence of mechanical and gas activation, is not homogeneous across the height of the mixer. In the upper part, horizontal flows prevail, flowing around the walls of the chamber and reducing axial circulation. In the lower part, however, the upward movement along the axis dominates, caused by the lifting force of the bubbles and mechanical drag from the rotor.

The formation of a multiphase flow in the mixing chamber is a continuous process of phase interaction, where no movement develops autonomously. Energy transfer between different movement scales, constant fluctuations in the internal structure, and the mutual penetration of liquid, solid, and gas phases change both the instantaneous flow characteristics and the overall stability of the system over time. In an environment that is constantly in a state of dynamic equilibrium, small-scale disturbances can alter large-scale circulation contours, while the general direction of primary flows determines the development of microstructural elements.

The gas phase, introduced through nozzles at the bottom of the chamber, actively participates in these processes. As noted by A.M. Sapata Rivera and colleagues, gas bubbles passing through the liquid medium not only create lifting forces that promote vertical movement of the mixture but also initiate the formation of convective contours that restructure the overall circulation structure. Such incorporation of gas into the internal dynamics of the flow enhances vertical mass transfer and prevents the formation of horizontal zones with high solid-phase concentrations, which are characteristic of mixers without aeration.

The structure of the distribution of gas bubbles in the chamber shows stratification by size, which forms additional levels of organization of the flow. As D. Frizo points out, large bubbles concentrate near the axis of the mixer, where the axial rise speed of the liquid is maximal, while smaller ones are distributed mainly in the radial direction, forming a network of micro-flows. These structures support effective mass exchange between phases and contribute to maintaining dynamic activity even in regimes of reduced turbulent energy in the primary flow.

The presence of such a dual distribution—large bubbles dominating along the axis and small bubbles scattered throughout the volume—provides a unique mass transfer dynamics: a combination of rapid vertical convective currents and slow horizontal micro-movements. This interaction of structures determines the mixer's ability to maintain suspension homogeneity and the stability of the hydrodynamic regime across a wide range of technological loads.

The structure of the multiphase flow in the mixer is in a constant state of change. The formation and destruction of local convective contours, the accumulation and dispersion of solid particles, and the shifting position of gas bubbles—all these processes occur continuously, altering the configuration of the system in the time dimension. Such non-stationarity makes numerical modelling challenging and explains the sensitivity of mixing processes to even slight changes in external parameters.

Increasing the intensity of gas aeration changes the nature of mixing not only by increasing the lifting force in the liquid medium but also through a profound restructuring of the internal flow structure. As the gas flow rate increases, the upward velocity in the center of the chamber strengthens, shifting the zone of maximum mixing toward the upper part of the mixer. At the same time, excessive gas lift intensity can generate unstable regimes: large bubbles push solid particles to the periphery, creating areas with local oversaturation near the walls and reducing the overall efficiency of mass transfer.

The mixing regime in a combined mixer is determined by the relationship between the rotor's rotational speed and the intensity of gas injection. Optimal working parameters allow for maintaining a uniform distribution of the solid phase throughout the chamber volume, preventing the formation of stagnant zones or areas with uneven concentration. Shifting this balance—toward excessive aeration or insufficient mechanical activation—changes the flow nature, leading to phase stratification and a gradual reduction in mixing efficiency.

Numerical modelling of multiphase processes offers the opportunity not only to describe the changing flow regimes but also to track the critical conditions at which the flow structure loses stability. Analyzing turbulent energy distribution, velocity fields, and solid inclusion concentrations in mixing chambers helps identify threshold values of operational parameters, beyond which the circulation character changes and the system's dynamic equilibrium is disrupted. Crossing these boundaries leads to a transformation of the flow, which directly impacts mixing efficiency.

In combined mixers, even small changes in rotor speed or gas flow rate lead to a restructuring of circulation contours. These changes are not limited to local zones but spread throughout the flow structure, altering velocity profiles and mass transfer processes. Establishing a new regime depends not only on the initial intensity of the disturbance but also on the system's ability to quickly return to a stable state without significant fluctuations.

Disruptions in the mixing regime in production conditions often lead to local aggregation of solid particles, the appearance of zones with reduced mass transfer, and a decrease in overall process efficiency. Such deviations can affect not only product properties but also the productivity of the production line, as even short-term disruptions in the flow structure change the kinetic parameters of reactions or the physico-chemical properties of the suspension. Using numerical modelling to create regime maps for mixers enables planning the system's operation within safe regimes and reducing the likelihood of unstable conditions in real operational conditions.

The formation of stagnant zones in the mixing volume is a result not only of decreased local turbulent energy but also of the complex interaction of phases on a micro level. The accumulation of solid particles near the chamber walls is the result of a combination of mechanical drag by turbulent eddies, gravitational settling, and insufficient compensation of these effects by the lifting force of gas bubbles. In cases of excessive bubble coalescence and a decrease in the total interfacial surface area, the efficiency of mass transfer is noticeably reduced.

Using CFD-DEM models allows not only visualizing the overall flows but also tracking individual particle trajectories, determining their average residence time in zones of active mixing, and identifying local concentration fluctuations. Under optimal working conditions, the average residence time of solid particles in the active turbulence zone is about 70–80% of the total movement time, indicating high mixing efficiency. A decrease in this figure signals the appearance of stagnant zones, which can significantly impact the final quality of the technological product.

Energy analysis of the mixer's operation shows that combining mechanical rotor rotation with gas aeration allows for reducing specific energy consumption without losing process efficiency. Gas bubbles, by aiding the rise of the liquid phase, partially compensate for the required mechanical energy, reducing the overall load on the rotor drive. This opens up the possibility for creating energy-efficient mixing systems capable of operating at high productivity with reduced energy consumption.

Parametric studies of the mixing chamber show that changes in its geometric proportions, without corresponding adjustment of operational characteristics, can significantly affect the flow structure. Reducing the chamber height or increasing its diameter without proper adjustment of rotor speed leads to weakening of vertical circulation and disruption of the force balance in the multiphase environment. Under these conditions, the risk of phase stratification increases: solid particles and gas bubbles accumulate in peripheral or bottom zones, and the mass transfer efficiency between phases decreases noticeably.

The flow structure in multiphase mixing systems is determined by the ratio between the chamber height, rotor diameter, and rotational speed. As D.A. Alaita notes, this relationship forms the stability of circulation contours and determines the nature of mass transfer within the mixing volume. Within the range of optimal parameters, the flow maintains phase uniformity and stability of the circulation structure without significant increases in energy costs, ensuring the necessary technological conditions over long periods.

Exceeding this balance, even to a small degree, alters the course of the process. Local zones with low mass transfer intensity form, where solid particles accumulate, and the gas phase forms clusters that fall out of the general circulation pattern. The development of such isolated structures leads to a gradual loss of multiphase flow uniformity, changing not only the mixing efficiency but also the rheological properties of the environment, affecting the stability of the technological process.

Understanding these relationships is not only of theoretical value. In the practice of designing mixing systems, the alignment of geometric and operational parameters determines the equipment's service life, energy efficiency level, and the stability of the suspension's technological characteristics.

At the general level, combined mixing of aqueous suspensions with solid and gas phases appears as a multi-level system of interactions. At each level—from the movement of individual particles to macroscopic circulation—specific mechanisms of mutual influence between phases are realized. Understanding these mechanisms through computational modelling not only allows for reconstructing the actual behavior of the flow but also for developing effective strategies to optimize technological processes in industry, focusing on increasing homogeneity, maintaining regime stability, and reducing energy consumption.

Conclusions

Computer simulation of the flow structure in a combined mixer for aqueous suspensions with solid and gas phases has made it possible to identify the patterns of multiphase flow formation in complex technological systems. The built CFD-DEM model reproduced the main physical processes accompanying mixing, including circulation loops, phase segregation, and the formation of recirculation zones.

The scientific novelty of the study lies in determining the critical parameters of the rotor rotation regime and the intensity of gas aeration, which ensure optimal homogenization of the solid and gas phases with minimal energy consumption. For mixers of this type, the relationship between the structure of turbulent characteristics and the spatial arrangement of gas bubbles and the local concentration of solid particles in different zones of the mixing chamber was established.

The practical significance of the obtained results lies in the possibility of using the built model for optimizing the structural parameters of mixers, calculating regime characteristics, and developing recommendations for improving suspension preparation systems in water treatment, chemical, and mining industries. Taking into account the peculiarities of phase circulation, turbulent energy distribution, and the behavior of solid particles in a multiphase environment allows for enhancing the energy efficiency of mixing processes and the stability of the final technological characteristics of the product.

Modelling multiphase flows is gradually moving beyond standard approaches and requires considering the deformation of gas bubbles in the flow dynamics. The change in the shape of the bubbles and their behavior under the influence of local conditions affects not only the microstructure of the medium but also determines the character of mass transfer processes across the entire mixing system. In regimes with high circulation intensity, where the properties of the medium change over time and space, such effects gain particular significance.

Along with bubble deformation, significant roles are played by processes of bubble coalescence and breakage, as well as the aggregation of solid particles. The change in the number of phase transitions and the appearance of new areas of non-uniformity in the suspension alters the mass transfer trajectories, which requires new approaches to numerical description. The development of models capable of integrating hydrodynamic and microstructural phenomena into a single computational picture is a logical direction for the development of this field.

Particular attention is paid to the variable rheological properties of the medium, as an increase in the solid component concentration changes the viscosity and manifests thixotropic effects. Such changes directly affect the development of turbulent structures, altering the local fluctuation energy and determining the stability of circulation loops over time.

Expanding computational models to include chemical reactions in a multiphase medium opens the possibility to describe not only hydrodynamic but also kinetic aspects of mixing. The interaction of flow and reaction processes in a combined computational scheme creates the basis for the development of new types of technological systems, where the optimization of energy and material resource usage becomes an integrated part of the overall dynamics of production.

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Комп'ютерне моделювання структури потоку у комбінованому змішувачі для водних суспензій з твердою та газовою фазами

У статті виконано огляд процесів комп'ютерного моделювання структури багатофазного потоку у змішувачах для водних суспензій із твердою та газовою фазами. Проаналізовано особливості взаємодії рідкої, твердої та газової фаз у змішувальних системах, а також визначено, як локальні швидкості, турбулентні флуктуації та реологічні властивості середовища впливають на характер циркуляції і масообміну. Починаючи з розвитку CFD-DEM методів, моделювання дозволило наблизити реконструкцію реальних процесів у змішувачах до тривимірної картини, однак складність реальної динаміки середовища досі вимагає вдосконалення моделей. Дослідження показують, що газова фаза не лише підтримує циркуляційні процеси, а й змінює локальні структури швидкості, і таким чином впливає на розподіл твердих частинок у потоці. Крім того, в процесі аналізу виявлено, що деформація бульбашок газу, їхня коалесценція і руйнування, а також агрегація твердого компонента призводять до утворення зон із різною інтенсивністю масообміну та локальними нерівномірностями концентрації фаз. Робота змішувача залежить від співвідношення висоти камери, діаметра ротора і швидкості його обертання, що визначає стабільність циркуляційних контурів і рівномірність розподілу фаз. Відхилення від оптимальних режимних характеристик призводить до розвитку нестійких зон, де накопичення твердих частинок і газових бульбашок порушує загальну ефективність процесу змішування. Окрему увагу приділено питанню впливу реологічних властивостей суспензії на турбулентні характеристики потоку, оскільки підвищення концентрації твердого компонента змінює в'язкість і впливає на локальну стійкість циркуляційних структур. У статті також розглянуто перспективи інтеграції хімічно-кінетичних процесів у обчислювальні моделі змішування, що відкриває можливості для створення нових технологічних рішень у промисловості. Таким чином чисельне моделювання змішувальних систем із багатофазним середовищем залишається ефективним інструментом для оптимізації сучасних виробничих процесів, спрямованих на підвищення енергоефективності та зниження технологічних втрат.

Ключові слова: CFD-DEM моделювання, багатофазні потоки, комбінований змішувач, масообмін, газові бульбашки, циркуляційні структури.

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