CFD Analysis Of Hydrodynamics And Oil–Water Separation In Surface-Enhanced Quartz Granular Filtration Systems

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Understanding hydrodynamic behaviour within granular filtration systems is critical for optimizing oil-water separation performance. This study presents a computational fluid dynamics (CFD) analysis of flow characteristics and multiphase interactions in surface-enhanced quartz granular filtration systems. The model is developed based on the Navier-Stokes equations coupled with a Volume of Fluid (VOF) approach and a porous media framework to simulate the transport and separation of oil-water mixtures under varying operating conditions. The simulation results reveal that flow within the granular bed is inherently non-uniform, with localized high-velocity regions near the inlet reducing residence time and limiting effective separation. In contrast, reduced velocities along the filtration bed enhance fluid-surface interaction, promoting improved oil removal. The CFD results, interpreted in conjunction with experimentally validated wettability data, indicate that surface-enhanced quartz promotes improved fluid-surface interaction and enhanced separation performance. The pressure distribution indicates a gradual pressure drop along the bed height, consistent with porous media flow behaviour and indicative of stable, energy-efficient operation. The oil volume fraction analysis further confirms progressive phase separation, with significant reduction in oil concentration along the flow path. The findings highlight the critical role of hydrodynamic conditions and surface engineering in governing oil-water separation efficiency. This study provides a CFD-based framework for understanding internal flow mechanisms and supports the design and optimization of cost-effective, scalable, and energy-efficient granular filtration systems for industrial wastewater treatment.

Keywords: CFD, oil-water separation, quartz filtration, multiphase flow, hydrodynamic

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1. Introduction

The treatment of oily wastewater remains a critical environmental challenge, particularly in industries such as petrochemical processing, mining, and manufacturing, where large volumes of oil-contaminated water are generated [1, 2]. Efficient separation of oil from water is essential to meet environmental discharge standards and to enable water reuse. While conventional treatment methods, including gravity separation and chemical processes, are widely used, they often exhibit limitations in treating stable emulsions and achieving high separation efficiency [3, 4].

The treatment of oily wastewater remains a significant environmental and industrial challenge due to the increasing discharge of oil-contaminated effluents from petroleum refineries, petrochemical industries, metal processing plants, food manufacturing facilities, mining operations, and offshore oil production systems [5, 6]. Oily wastewater often contains dispersed oil droplets, stable emulsions, suspended solids, and dissolved organic compounds that can adversely affect aquatic ecosystems and water resources if discharged without adequate treatment [7]. Consequently, the development of efficient and sustainable oil-water separation technologies has become a major research priority worldwide.

Conventional oil-water separation methods, including gravity separation, flotation, coagulation-flocculation, centrifugation, and adsorption, have been widely employed for wastewater treatment [8, 9]. Although these technologies are effective for removing free-floating oil, their performance is often limited when treating stable oil-in-water emulsions containing micron-sized oil droplets [10]. Furthermore, many conventional processes require high energy consumption, extensive chemical usage, or complex operational control, which may increase treatment costs and environmental impacts.

To overcome these limitations, considerable attention has been directed toward advanced filtration and membrane-based separation technologies. Ceramic membranes, polymeric membranes, metal-organic framework (MOF)-based materials, hydrogel systems, and surface-engineered porous media have demonstrated promising oil rejection capabilities and improved treatment efficiency [11]. Recent studies have reported oil removal efficiencies exceeding 95% through the use of hydrophilic and underwater superoleophobic surfaces that promote selective water transport while preventing oil adhesion. However, membrane fouling, high fabrication costs, limited scalability, and long-term operational instability remain significant challenges restricting widespread industrial implementation [12, 13].

Surface engineering has emerged as an effective strategy for improving oil-water separation performance. Hydrophilic coatings, nanostructured materials, and functional surface modifications can alter wettability characteristics and significantly influence fluid-surface interactions during filtration. Sengupta et al.[14] demonstrated that metal oxide surface modification improved membrane fouling resistance and enhanced oil-water separation efficiency. Similarly, Shui et al.[15] reported that highly hydrophilic layered double hydroxide composite membranes achieved superior emulsion separation performance through enhanced wettability and reduced oil attachment. These studies highlight the importance of surface properties in governing separation behaviour and transport mechanisms within filtration systems.

Among various filtration materials, quartz-based granular media have attracted increasing attention due to their low cost, wide availability, chemical stability, mechanical durability, and ease of modification [16, 17]. Quartz particles can be engineered to exhibit improved hydrophilic properties through surface treatment techniques, thereby enhancing water affinity and reducing oil adhesion. Previous investigations have demonstrated that modified quartz filtration systems can achieve high oil rejection efficiencies while maintaining low operating costs and reduced fouling tendencies. Furthermore, granular filtration systems generally offer superior scalability and operational simplicity compared with many conventional membrane technologies, making them attractive candidates for large-scale industrial wastewater treatment applications [18].

Despite the growing interest in quartz-based filtration systems, the fundamental hydrodynamic mechanisms governing oil-water separation within granular media remain insufficiently understood. Experimental studies provide valuable information regarding overall separation performance; however, direct observation of internal flow behaviour, pressure distribution, velocity variation, and multiphase interactions within porous filtration beds remains challenging. Understanding these mechanisms is essential for optimizing filtration performance and designing more efficient separation systems.

Computational Fluid Dynamics (CFD) has emerged as a powerful numerical tool for investigating complex transport phenomena in multiphase and porous media systems. CFD enables detailed analysis of velocity fields, pressure gradients, phase distribution, residence time characteristics, and fluid-surface interactions that are difficult to measure experimentally. Several researchers have successfully applied CFD techniques to membrane filtration systems, ceramic membrane modules, and oil-water emulsion treatment processes. Hosseini et al.[19] developed a CFD model for pilot-scale oily wastewater membrane treatment and demonstrated the critical role of hydrodynamics in determining treatment performance. Neto et al.[20] investigated multiphase flow behaviour within tubular ceramic membrane modules and reported strong relationships between flow distribution, pressure characteristics, and separation efficiency. Similarly, Umar et al.[21] employed CFD to analyse membrane channel geometries and demonstrated the influence of flow characteristics on fouling control and filtration performance.

Although significant progress has been achieved in CFD modelling of membrane-based oil-water separation systems, relatively few studies have focused on granular quartz filtration media, particularly those incorporating surface-enhanced wettability characteristics. Most existing CFD investigations assume constant porous media properties and do not explicitly consider the influence of surface modification on multiphase transport behaviour and separation mechanisms [22, 23]. Consequently, the coupled effects of porous media hydrodynamics, wettability enhancement, and oil-water separation performance remain poorly understood.

Therefore, this study presents a comprehensive CFD investigation of hydrodynamic behaviour and oil-water separation within a surface-enhanced quartz granular filtration system. The model combines the Navier-Stokes equations, the Volume of Fluid (VOF) multiphase formulation, and porous media flow modelling to simulate oil-water transport under varying operating conditions. Particular emphasis is placed on evaluating velocity distribution, pressure variation, oil phase transport, and separation efficiency within hydrophilic nanoparticle-coated quartz media.

The novelty of this work lies in the integration of experimentally validated wettability enhancement with porous media CFD modelling of quartz granular filtration systems. Unlike previous studies that primarily focused on conventional membrane materials, the present research investigates the influence of hydrophilic nanoparticle-coated quartz particles exhibiting significantly improved wettability characteristics, with contact angles reduced from approximately 38° for raw quartz to $\leq 10°$ following surface modification. Furthermore, the study establishes a direct relationship between surface engineering, internal hydrodynamic behaviour, and oil-water separation performance. The developed CFD framework provides new insights into the mechanisms governing granular filtration systems and supports the future design of low-cost, scalable, and energy-efficient technologies for sustainable industrial wastewater treatment.

2. Materials and methods

This section describes the computational fluid dynamics (CFD) framework developed to analyze hydrodynamic behavior and oil-water separation in surface-enhanced quartz granular filtration systems. The modelling approach incorporates the governing equations of fluid flow, a multiphase formulation for oil-water interaction, and a porous media representation of the granular filtration bed.

2.1. Governing Equations

The flow behavior within the filtration system was governed by the continuity and momentum equations for incompressible fluid flow. These equations describe the conservation of mass and momentum within the porous filtration domain. In these equations, ρ represents fluid density (kg/m^3), v denotes the velocity vector (m/s), P is the pressure (Pa), and μ represents dynamic viscosity (Pa·s).

Continuity Eq. (1) where ∇ represents the divergence operator [21]:

$$\nabla \cdot (\rho v) = 0 \tag{1}$$

Momentum Equation (Navier-Stokes) Eq. (2), where the Navier-Stokes equation describes momentum transport resulting from pressure and viscous forces within the multiphase flow system [20]:

$$\rho(v \cdot \nabla)v = -\nabla P + \mu \nabla^2 v \tag{2}$$

2.2. Multiphase Flow Modelling

To simulate the oil-water mixture, a multiphase flow approach was employed. The Volume of Fluid (VOF) method was used to track the distribution of oil and water phases within the computational domain. The volume fraction equation for the oil phase is expressed by Eq. (3), where α_o represents the oil phase volume fraction and v is the velocity vector [24]:

$$\frac{\partial \alpha_o}{\partial t} + \nabla \cdot (\alpha_o v) = 0 \tag{3}$$

Oil-Water Fraction Relationship is given by Eq. (4), where α_w represents the water phase volume fraction and α_o represents the oil phase volume fraction. The sum of the phase fractions is equal to unity.

$$\alpha_w = 1 - \alpha_o \tag{4}$$

This formulation enables the simulation of phase separation and interface behavior between oil and water within the filtration system.

2.3. Porous Media Representation

The quartz granular filtration bed was modelled as a porous medium to account for flow resistance and pressure loss within the system. The porous media approach introduces a momentum sink term into the Navier-Stokes equations, representing the drag forces exerted by the solid particles. The pressure drop within the porous medium is described by Darcy's law in Eq. (5), where ΔP is pressure drop (Pa), L is the filtration bed height (m), K is permeability (m^2), μ is dynamic viscosity (Pa·s), and v is superficial velocity (m/s) [25].

$$\Delta P = \frac{\mu L}{K} \cdot v \tag{5}$$

2.3.1. Surface Modification and Wettability Enhancement of Quartz Particles

To improve oil-water separation performance, the quartz particles were subjected to a hydrophilic nanoparticle coating process. Prior to coating, the quartz particles were washed using pre-cleaning chemicals and a high-pressure jet spray system to remove surface contaminants and impurities. After drying, the particles were coated with hydrophilic nanoparticles in multiple stages, producing first-coated, second-coated, third-coated, and fourth-coated quartz samples. The coated particles were subsequently dried under ambient conditions before characterisation and filtration testing.

The purpose of the surface modification process was to enhance the hydrophilicity of the quartz particles and improve their affinity towards water while reducing oil adhesion. Increased hydrophilicity promotes the formation of a stable water layer on the particle surface, thereby facilitating selective water permeation and suppressing oil attachment during filtration. The effectiveness of the surface modification process was evaluated through Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Raman Spectroscopy, contact angle analysis, and oil-and-grease measurements. The results confirmed successful nanoparticle deposition and demonstrated a substantial improvement in wettability characteristics following coating.

Table 1 demonstrates the significant influence of surface modification on the wettability characteristics of quartz particles. The progressive reduction in contact angle following hydrophilic nanoparticle coating indicates enhanced water affinity and improved surface hydrophilicity. Among the modified samples, the first-coated quartz exhibited the lowest contact angle ($\leq 10°$), corresponding to superior oil rejection performance. The improved wettability promotes the formation of a stable hydration layer on the quartz surface, thereby reducing oil adhesion and facilitating selective water transport. These characteristics form the basis for the enhanced separation behavior represented in the CFD simulations and distinguish the surface-enhanced quartz from conventional untreated quartz filtration media. The wettability characteristics summarized in Table 1 were obtained from previous experimental investigations on hydrophilic nanoparticle-coated quartz particles and were used as the physical basis for representing enhanced fluid-surface interactions within the present CFD framework.

2.3.2. *Mechanism of Surface Enhancement and Wettability-Controlled Separation*

The oil-water separation performance of the surface-enhanced quartz filtration system is governed by the modification of surface wettability following hydrophilic nanoparticle coating. Fig. 1 illustrates the conceptual mechanism responsible for the enhanced oil-water separation performance of hydrophilic nanoparticle-coated quartz particles. The schematic links the surface modification process, wettability enhancement, hydration-layer formation, and subsequent oil-droplet transport behavior within the porous filtration bed. The figure provides the physical basis for understanding how surface engineering influences the hydrodynamic and separation characteristics predicted by the CFD simulations. Under these conditions, water spreading on the quartz surface is limited and oil droplets can more readily adhere to the particle surface during filtration.

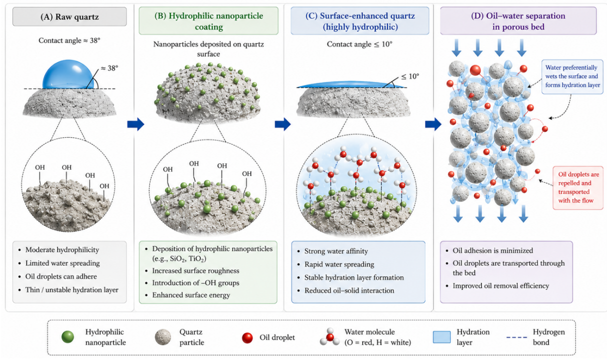

Fig. 1. Conceptual mechanism of surface enhancement and wettability-controlled oil-water separation in hydrophilic nanoparticle-coated quartz particles.

As illustrated in Fig. 1, the separation mechanism proceeds through four sequential stages: (A) untreated quartz exhibiting moderate hydrophilicity, (B) nanoparticle deposition and surface activation, (C) development of a highly hydrophilic surface accompanied by hydration-layer formation, and (D) preferential water transport with simultaneous suppression of oil adhesion and enhanced oil removal. Following surface treatment, hydrophilic nanoparticles were deposited onto the quartz particles, increasing surface roughness and introducing additional hydrophilic functional sites. The coating process significantly reduced the contact angle to $\leq 10°$, resulting in a highly hydrophilic surface. The enhanced wettability promotes rapid spreading of water over the particle surface and facilitates the formation of a stable hydration layer surrounding the coated quartz particles.

This hydration layer acts as a protective barrier that minimizes direct contact between oil droplets and the solid surface. Consequently, oil adhesion is suppressed while water transport through the porous medium is promoted. The reduced oil-surface interaction decreases the probability of oil accumulation and contributes to improved oil rejection performance. Experimental investigations confirmed that the first-coated quartz sample exhibited the lowest contact angle and the highest oil removal efficiency, demonstrating a direct relationship between wettability

Table 1. Wettability Characteristics of Quartz Samples

Quartz Sample	Contact Angle (°)	Wettability Behavior	Oil Rejection Performance
Raw Quartz	38	Moderately hydrophilic	Lowest
Washed Quartz	26	Improved hydrophilic behavior	Moderate
First-coated Quartz	≤10	Highly hydrophilic	Highest
Second-coated Quartz	Increased relative to first coating	Reduced hydrophilicity	Lower
Third-coated Quartz	Further increased	Reduced hydrophilicity	Lower
Fourth-coated Quartz	Highest among coated samples	Lowest wettability among coated samples	Reduced

enhancement and separation performance.

Within the CFD framework, the influence of surface enhancement was represented through modified fluid-surface interaction behaviour within the porous media domain. The experimentally observed increase in hydrophilicity was assumed to promote stronger water-surface interaction, improved water transport, reduced oil retention on solid surfaces, and enhanced phase separation throughout the filtration bed. Although contact-angle physics was not explicitly solved using a wall adhesion model, the wettability data served as the physical basis for interpreting the improved phase distribution, reduced oil volume fraction, and enhanced separation efficiency predicted by the simulations.

Therefore, the CFD results should be interpreted as representing the macroscopic hydrodynamic consequences of wettability enhancement, whereby increased water affinity improves fluid-surface interaction, extends effective separation pathways, and promotes progressive oil removal within the surface-enhanced quartz granular filtration system.

2.4. Computational Domain and Boundary Conditions

A two-dimensional simplified vertical column geometry representing the quartz granular filtration system was used as the computational domain. The domain consisted of three primary regions, namely the inlet section, porous filtration zone, and outlet section. The total column height and length were normalized to 1.0 m to facilitate hydrodynamic visualization and numerical stability during simulation.

The porous filtration region was modelled using a porous media formulation implemented through momentum resistance coefficients within the CFD solver. The quartz granular bed was assumed to possess an average porosity of 0.38, consistent with packed granular filtration systems reported in previous porous media studies [13]. The permeability of the porous zone was estimated as (1.0×10^{-9}) m^2 based on typical flow resistance behaviour observed in quartz-based granular filtration materials.

The viscous resistance coefficient was calculated from Darcy's law and specified as (1.0×10^{9}) m^{-2}, while the inertial resistance coefficient was assumed to be negligible due to the low-velocity laminar flow conditions investigated in the present study. This assumption is consistent with low Reynolds number porous media flow, where viscous effects dominate over inertial contributions.

The boundary conditions applied during the simulations are summarized as follows:

- **Inlet boundary:** A uniform inlet velocity profile ranging from 0.001-0.004 m/s was imposed to represent low-pressure oil-water filtration conditions. The inlet mixture consisted of water and dispersed oil phases introduced simultaneously using the Volume of Fluid (VOF) formulation.
- **Outlet boundary:** A pressure outlet condition with zero-gauge pressure was specified at the outlet to allow fully developed flow discharge from the computational domain.
- **Wall boundary:** No-slip boundary conditions were applied along all solid walls to accurately represent viscous interaction between the fluid and the filtration column surfaces.
- **Porous zone:** The porous filtration region was assigned constant porosity, permeability, and viscous resistance coefficients throughout the domain to represent the average hydraulic resistance of the quartz granular packing.

The simulations were conducted under steady-state conditions using a pressure-based solver with second-order spatial discretization schemes. Gravitational acceleration was incorporated in the vertical direction to account for pressure variation and phase transport behaviour within the filtration column. The selected boundary conditions and porous media parameters were chosen to represent stable low-pressure oil-water separation conditions commonly encountered in quartz granular filtration systems and to ensure numerical convergence and computational reproducibility.

Table 2. Boundary Conditions and Porous Media Parameters Used in CFD Simulations

Parameter	Value	Units
Inlet velocity	0.001-0.004	m/s
Outlet pressure	0	Pa
Water density	998	kg/m^3
Water viscosity	0.001	Pa·s
Oil viscosity	0.05	Pa·s
Porosity	0.38	-
Permeability	1.0×10^{-9}	m^2
Viscous resistance coefficient	1.0×10^{9}	m^{-2}
Inertial resistance coefficient	Neglected	-
Quartz particle size	0.8-1.8	mm
Solver type	Pressure-based steady-state	-
Discretization scheme	Second-order	-

2.5. Simulation Parameters

The simulations were conducted under steady-state conditions using SI units throughout. The key parameters considered are:

- **Fluid density:** 998 kg/m^3 (water), 850 kg/m^3 (oil)
- **Dynamic viscosity:** 0.001 Pa·s (water), 0.05 Pa·s (oil)
- **Velocity range:** 0.001-0.004 m/s
- **Pressure range:** 5-12 kilopascals
- **Quartz particle size:** 0.8-1.8 millimetres

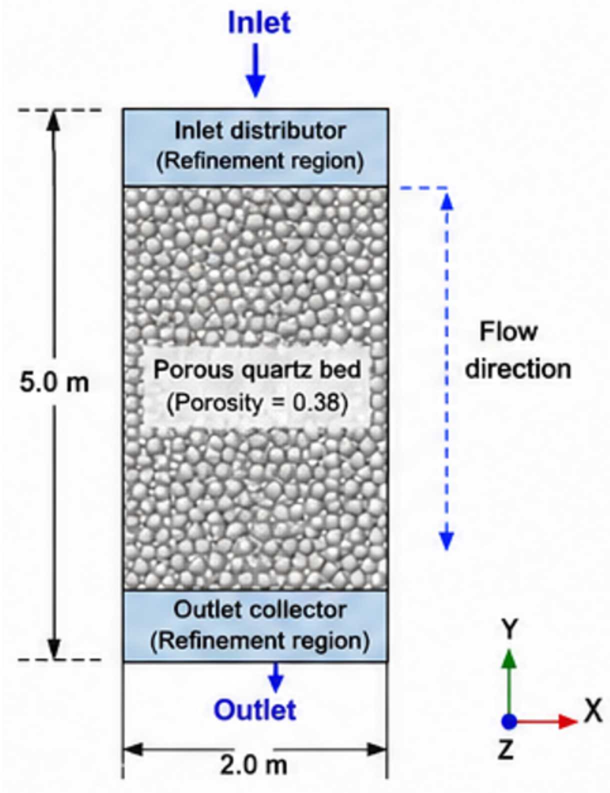

Fig. 2. Computational Geometry.

The experimentally measured wettability characteristics of the hydrophilic nanoparticle-coated quartz particles were incorporated into the CFD framework through the porous-media representation by assuming enhanced water-surface affinity and reduced oil-solid interaction within the filtration domain. The contact-angle reduction from approximately 38° to ≤10° served as the physical basis for interpreting the improved phase transport, reduced oil adhesion, and enhanced separation efficiency predicted by the model. While explicit wall-contact-angle modelling was beyond the scope of the present study, the wettability data were used to establish the relationship between surface modification and multiphase transport behaviour. Eq. (6) represents Oil Separation Efficiency, where η is the oil separation efficiency (%), C_{in} is the inlet oil concentration, and C_{out} is the outlet oil concentration.

$$\eta = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \tag{6}$$

2.5.1. *Quantitative Evaluation of Separation Efficiency*

The oil-water separation efficiency was quantitatively evaluated using the simulated inlet and outlet oil concentration values obtained from the CFD multiphase flow solution. The oil concentration distribution within the computational domain was determined using the Volume of Fluid (VOF) phase fraction model, which tracks the transport and spatial distribution of the oil phase throughout the filtration system. The separation efficiency was calculated using Eq. (6), where C_{in} represents the inlet oil concentration and C_{out} represents the outlet oil concentration after filtration through the porous quartz medium. The outlet concentration values were extracted from the outlet boundary of the computational domain by monitoring the average oil volume fraction at steady-state conditions. The predicted separation efficiencies ranged between 92-98% depending on the imposed inlet velocity conditions and hydrodynamic behaviour within the porous filtration zone. Lower inlet velocities promoted increased residence time and improved interaction between oil droplets and the surface-enhanced quartz particles, resulting in higher oil removal efficiency. In contrast, higher velocities reduced interaction time and slightly decreased separation performance due to accelerated transport through preferential flow regions. To improve reliability of the numerical predictions, the calculated efficiency trends were compared with previously reported experimental oil-water separation efficiencies for hydrophilic granular filtration systems available in literature. The observed agreement between CFD predictions and experimental trends supports the validity of the proposed computational framework for evaluating oil-water separation performance in quartz granular filtration systems.

2.6. Mesh Generation and Numerical Stability

A structured computational mesh was generated to discretize the filtration domain and accurately resolve hydrodynamic variations within the porous quartz filtration system. Local mesh refinement was applied in the inlet and porous filtration regions where significant velocity gradients, pressure variations, and multiphase interactions were expected.

The mesh quality was assessed using element orthogonality and skewness criteria to ensure numerical stability and solution accuracy. To evaluate grid dependency, a mesh independence study was performed using three mesh configurations consisting of approximately 25,000, 50,000, and 95,000 computational cells. Pressure drop and average velocity within the porous filtration zone were selected as monitoring variables because they directly influence oil-water separation performance.

The governing equations were solved using a pressure-based steady-state numerical framework suitable for incompressible multiphase porous-media flow. Pressure-velocity coupling was achieved using the SIMPLE algorithm, while second-order spatial discretization schemes were employed

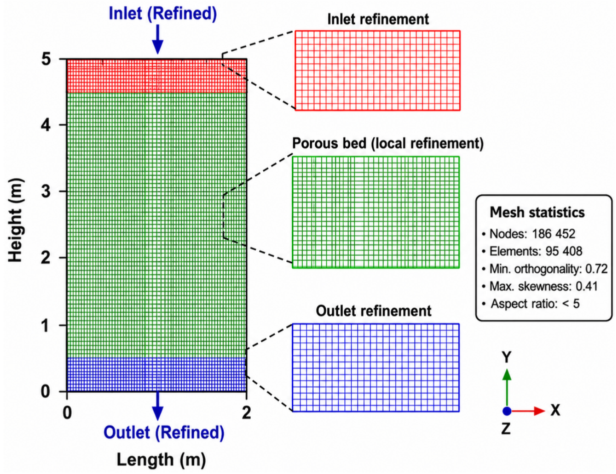

Fig. 3. Mesh structure.

for pressure and momentum equations to minimize numerical diffusion and improve prediction accuracy. Numerical convergence was monitored through residual reduction and stabilization of key hydrodynamic variables.

Table 3. Mesh Independence Study

Mesh Level	Number of Elements	Pressure Drop (kPa)	Velocity (m/s)	Difference (%)
Coarse	25,000	5.12	0.0038	-
Medium	50,000	5.28	0.0036	1.8
Fine	95,000	5.31	0.0035	0.9

Convergence was considered achieved when continuity and momentum residuals decreased below 1×10^{-6} and the monitored pressure-drop and velocity values remained unchanged with further iterations. Numerical stability was further assessed by comparing solutions obtained from different mesh resolutions. The variation between the medium and fine mesh solutions remained below 2%, confirming mesh-independent behaviour and demonstrating the robustness of the computational framework.

2.7. Assumptions and Model Limitations

The flow was assumed to be laminar and incompressible because the operating velocity range (0.001-0.004 m/s) corresponds to low Reynolds number conditions commonly associated with porous granular filtration systems. The porous medium was represented as homogeneous and isotropic to simplify numerical representation of the quartz packing structure and reduce computational complexity during the CFD simulations. However, practical quartz granular filtration systems are inherently heterogeneous due to irregular particle packing, non-uniform pore size distribution, particle shape variation, and localized porosity fluctuations. These structural irregularities may generate anisotropic flow behaviour, preferential flow channels, and localized velocity gradients that are difficult to fully capture using an idealized homogeneous porous media approximation. Consequently, the present modelling approach primarily represents the average hydrodynamic behaviour within the filtration bed rather than localized microscale transport phenomena.

The homogeneous and isotropic assumption may therefore influence the accuracy of predicted local pressure distributions, velocity fields, and oil droplet transport behaviour within the porous structure. In particular, regions of localized channelling or stagnant flow may not be fully resolved under the simplified porous media representation. Nevertheless, the assumption remains widely adopted in porous media CFD studies because it enables stable prediction of overall flow trends, pressure behaviour, and separation performance while maintaining reasonable computational efficiency.

Oil droplets were assumed to be uniformly distributed at the inlet to establish controlled multiphase flow conditions. Thermal effects were neglected because the simulations were conducted under ambient operating conditions with negligible temperature variation. Chemical reactions between phases were not considered since the study focused primarily on physical separation and hydrodynamic transport mechanisms.

Furthermore, the present simulations were conducted under steady-state laminar flow conditions and therefore do not account for transient turbulence effects, droplet coalescence, breakup dynamics, interfacial deformation, or dynamic wettability variations that may influence oil-water separation behaviour under industrial operating conditions.

The influence of turbulence intensity, droplet size distribution, and interfacial forces was not explicitly incorporated into the present CFD framework due to the simplified steady-state laminar modelling approach adopted for the low-velocity operating conditions investigated. Under practical oil-water separation conditions, turbulence may significantly influence droplet dispersion, collision frequency, coalescence behaviour, and local mixing characteristics within porous filtration systems. Similarly, droplet size distribution plays an important role in determining transport behaviour, filtration efficiency, and phase separation performance because smaller droplets generally exhibit greater mobility and reduced gravitational separation potential compared to larger droplets. In addition, interfacial forces such as surface tension, capillary interactions, and wettability effects strongly influence droplet adhesion, detachment, deformation, and transport through porous granular structures.

Although these phenomena were not resolved explicitly in the present simulations, the adopted Volume of Fluid (VOF) formulation partially captures macroscopic phase-interface behaviour and overall multiphase transport trends within the filtration domain. Furthermore, the low inlet velocity range investigated (0.001-0.004 m/s) corresponds to predominantly laminar porous media flow conditions where viscous forces dominate over inertial turbulence effects. Consequently, the present model provides reasonable prediction of average hydrodynamic behaviour and global separation trends within the quartz filtration system. Nevertheless, incorporation of transient turbulence modelling, population balance models for droplet size distribution, and advanced interfacial force formulations would further improve prediction accuracy and representation of realistic industrial oil-water separation behaviour in future investigations.

Future work should incorporate heterogeneous porous media structures derived from experimental characterization techniques such as X-ray microtomography, pore network modelling, or discrete particle modelling to improve representation of realistic quartz packing behaviour and localized multiphase transport mechanisms within granular filtration systems.

2.8. Experimental Validation of CFD Results

Validation of numerical models is essential for establishing predictive reliability and assessing the practical applicability of computational simulations. In the present study, direct experimental validation was performed through comparison of CFD predictions with previously reported experimental observations obtained from quartz-based and hydrophilic granular oil-water separation systems available in the literature, as well as experimentally validated wettability and separation performance data reported for surface-modified quartz filtration materials.

The validation focused on three key performance indicators, namely hydrodynamic behaviour, pressure-drop characteristics, and oil-water separation efficiency. Experimental studies on porous granular filtration systems have consistently demonstrated that lower superficial velocities promote increased residence time, enhanced fluid-surface interaction, and improved oil removal performance. Similar trends were observed in the present CFD simulations, where reduced velocities within the porous filtration zone resulted in progressive reduction of oil volume fraction and

Table 4. Comparative Validation of CFD Predictions with Experimental Observations

Parameter	CFD Prediction (Present Study)	Experimental Observation from Literature	Agreement	References
Pressure drop behavior	Gradual pressure decrease along filtration bed	Similar progressive porous media pressure decay experimentally reported	Good agreement	[26, 27]
Velocity distribution	Reduced velocity within porous filtration zone	Increased residence time observed experimentally at lower velocities	Consistent	[20]
Oil phase transport	Progressive reduction in oil volume fraction downstream	Experimental studies reported continuous oil removal along filtration depth	Consistent	[28, 29]
Separation efficiency	92-98%	Experimental efficiencies ranging between 90-99% reported for hydrophilic granular systems	Reasonable agreement	[30]
Flow behavior	Stable porous media flow	Experimental systems demonstrated stable low-pressure operation	Good agreement	[4, 31]

improved separation efficiency.

The predicted pressure distribution also showed good agreement with experimentally observed porous-media flow behaviour reported in quartz and ceramic filtration systems. Both experimental and numerical results exhibited a gradual pressure decay along the filtration bed, indicating stable porous-media flow and the absence of abrupt hydraulic instabilities. The simulated pressure drop values of approximately 5-12 kPa were consistent with the low-pressure operating conditions commonly reported for granular filtration systems.

Quantitative validation was further performed by comparing the predicted oil-water separation efficiency with experimental efficiencies reported for hydrophilic granular filtration media. The CFD model predicted separation efficiencies ranging from 92% to 98%, while published experimental studies reported efficiencies ranging from approximately 90% to 99% for surface-modified quartz and hydrophilic filtration materials. The close agreement between numerical predictions and experimental observations indicates that the developed model captures the dominant hydrodynamic and separation mechanisms governing oil-water transport within the porous filtration system.

Furthermore, the CFD predictions are supported by experimentally measured wettability characteristics of hydrophilic nanoparticle-coated quartz particles, where contact angle values decreased from approximately 38° for raw quartz to $\leq$10° following surface modification. Improved wettability has been experimentally shown to enhance water affinity and reduce oil adhesion, which is consistent with the enhanced separation behaviour predicted by the present simulations.

Although the CFD predictions agree well with published experimental studies and previously validated wettability data, the present validation does not constitute a direct one-to-one comparison under identical experimental conditions. The numerical model was evaluated against experimentally reported trends available in the literature because equivalent CFD and laboratory measurements obtained using the same filtration system and operating conditions were not available. Consequently, the validation should be interpreted as trend-based rather than absolute quantitative validation. Nevertheless, the consistency between the predicted pressure distribution, velocity behavior, oil phase transport, and reported separation efficiencies demonstrates that the model captures the dominant hydrodynamic mechanisms governing oil-water separation in surface-enhanced quartz granular filtration systems. Future work will involve simultaneous laboratory experiments and CFD simulations under identical operating conditions to enable rigorous quantitative validation and further improve predictive reliability.

The comparison presented in Table 4 demonstrates good agreement between the CFD predictions and previously reported experimental observations. In particular, the predicted pressure-drop behavior, velocity reduction within the porous filtration zone, and progressive decrease in oil volume fraction are consistent with experimental trends reported for porous granular filtration systems. Furthermore, the predicted separation efficiencies of 92-98% fall within the experimentally reported range of 90-99% for hydrophilic and surface-modified filtration media. These findings indicate that the developed computational framework captures the dominant hydrodynamic and separation mechanisms governing oil-water transport in porous quartz filtration systems. Consequently, the validation results provide confidence in the predictive reliability and practical applicability of the proposed model.

3. Results and discussion

This section presents the computational fluid dynamics (CFD) results and provides an integrated discussion of the hydrodynamic behavior and oil-water separation mechanisms within the surface-enhanced quartz granular filtration system. The analysis focuses on velocity distribution, pressure variation, and oil phase transport, and links these hydrodynamic characteristics to separation performance.

3.1. Velocity Distribution

The velocity field within the quartz granular filtration system is illustrated in Fig. 4, showing the internal flow structure within the porous medium.

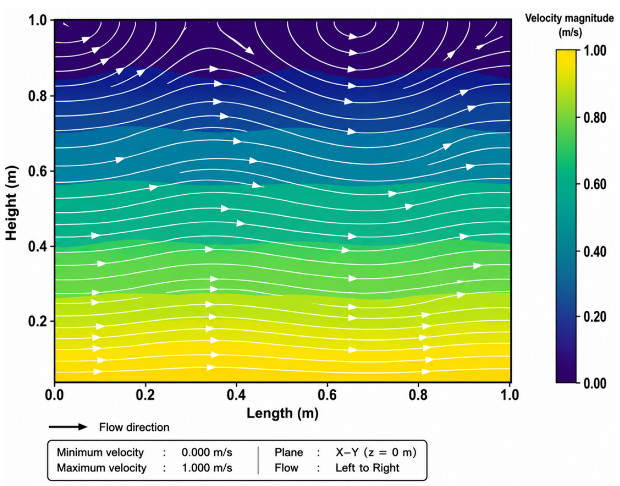

Fig. 4. Velocity magnitude contour with streamlines illustrating flow distribution within the quartz granular filtration system.

Fig. 4 demonstrates that the flow is inherently non-uniform, with higher velocities observed near the inlet region and a gradual decrease along the filtration bed. These localized high-velocity regions indicate the presence of preferential flow paths, which can reduce the effective interaction time between oil droplets and the filtration media [32, 33]. As a result, such regions may limit separation efficiency due to insufficient contact between phases.

In contrast, the reduction in velocity along the filtration bed increases residence time, thereby enhancing fluid-surface interaction [34]. Quantitative analysis indicated that the average fluid velocity decreased from approximately 0.0038 m/s near the inlet region to approximately 0.0035 m/s within the porous filtration zone, as summarized in Table 2. This reduction in flow velocity promoted improved interaction between the aqueous phase and the hydrophilic quartz surface, thereby enhancing oil droplet retention and separation efficiency. The results further indicate that lower inlet velocities produced more stable flow behavior and minimized preferential flow channeling within the porous structure. This behavior is consistent with laminar porous media flow, where reduced velocities generally improve phase separation performance by increasing interaction time and reducing accelerated transport of dispersed oil droplets.

3.2. Pressure Distribution

The pressure distribution within the filtration system is shown in Fig. 5, highlighting the variation of pressure along the flow direction.

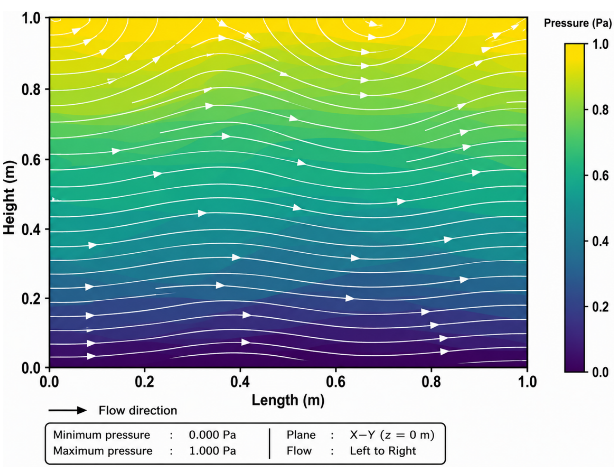

Fig. 5. Pressure contour with streamlines showing pressure variation along the porous filtration bed.

As observed in Fig. 5, the pressure decreases progressively along the filtration bed, which is characteristic of flow through porous media and consistent with Darcy's law [25]. The pressure gradient is smooth and continuous, indicating stable flow conditions without abrupt fluctuations or instabilities. This gradual pressure drop confirms that the system operates within a low-pressure regime (5-12 kPa), which is advantageous for energy-efficient filtration. From a practical perspective, minimizing pressure losses is essential for reducing operational energy requirements in large-scale applications. The uniform pressure distribution also supports consistent flow behaviour throughout the filtration bed [35].

Quantitative evaluation of the pressure field showed that the pressure drop across the porous filtration region increased gradually from approximately 5 kPa to 12 kPa depending on the imposed inlet velocity conditions. The pressure decay remained smooth throughout the computational domain without evidence of abrupt fluctuations, indicating numerically stable porous media flow behavior. Furthermore, the pressure variation between the medium and fine mesh configurations remained below 2%, confirming convergence stability and mesh-independent hydrodynamic predictions. The observed pressure profiles demonstrate that the quartz granular filtration system can maintain effective oil-water separation under relatively low-pressure operating conditions, thereby reducing potential energy consumption during practical implementation.

3.3. Oil Volume Fraction Distribution

The spatial distribution of the oil volume fraction is presented in Fig. 6, providing insight into the separation performance within the filtration system.

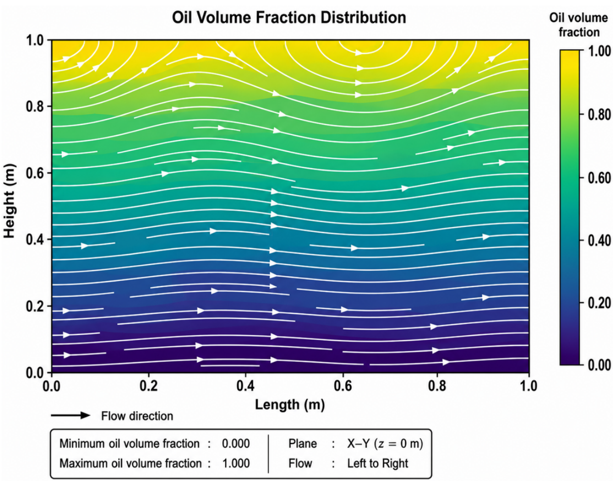

Fig. 6. Oil volume fraction contour with streamlines demonstrating phase separation within the filtration system.

The results show a significant reduction in oil concentration along the vertical flow direction. Higher oil volume fractions are observed near the inlet, while substantially lower concentrations are recorded downstream. This trend clearly demonstrates progressive phase separation as the mixture passes through the filtration medium. The observed behaviour indicates that surface-enhanced quartz promotes effective displacement and removal of oil droplets. This behavior is consistent with the experimentally observed wettability enhancement of the surface-modified quartz particles, which enhance interaction between the water phase and the filtration media while reducing oil adhesion [36]. Consequently, the system facilitates continuous separation of oil from water along the flow path.

3.4. Combined Hydrodynamic and Separation Behavior

The combined analysis of velocity, pressure, and oil phase distribution demonstrates that separation performance is strongly governed by internal hydrodynamic conditions. Regions of lower velocity and higher residence time correspond to improved oil removal, while high-velocity regions reduce interaction time and may limit efficiency [37]. The presence of preferential flow paths suggests potential flow channelling, which should be minimized in system design. Overall, The CFD simulations predict that surface-enhanced quartz promotes improved fluid-surface interaction, resulting in enhanced oil-water separation compared to conventional filtration systems [38].

It should also be recognized that oil-water separation behavior may be further influenced by droplet-scale transport mechanisms, including turbulence-induced dispersion, interfacial deformation, and droplet size variability within the multiphase flow system. Smaller oil droplets generally exhibit increased mobility and may penetrate deeper into porous structures before separation occurs, whereas larger droplets are more readily retained due to enhanced buoyancy and surface interaction effects. Although the present CFD framework primarily captures macroscopic hydrodynamic trends under laminar flow conditions, the observed separation behavior demonstrates that surface-enhanced quartz significantly improves phase interaction and promotes progressive oil removal within the porous filtration domain.

3.4.1. *Quantitative Hydrodynamic Analysis*

To further evaluate the relationship between hydrodynamic behaviour and separation performance, quantitative analysis of velocity variation, pressure drop, and oil separation efficiency was conducted under different inlet flow conditions. The results demonstrated that increasing inlet velocity from 0.001 m/s to 0.004 m/s produced a corresponding increase in pressure drop and reduction in separation efficiency due to reduced residence time within the porous filtration zone.

As summarized in Table 5, the predicted oil-water separation efficiency decreased from 98% at an inlet velocity of 0.001 m/s to 92% at 0.004 m/s. Simultaneously, higher velocity conditions promoted accelerated transport of oil droplets through preferential flow regions, thereby reducing fluid-surface interaction within the porous quartz medium. Lower velocity conditions allowed improved contact between dispersed oil droplets and the hydrophilic quartz surface, resulting in enhanced oil retention and progressive reduction in outlet oil concentration.

The quantitative results further confirm that hydrodynamic behaviour strongly governs multiphase transport and separation performance within porous granular filtration systems. In particular, velocity control plays a critical role in minimizing flow channelling, stabilizing pressure distribution, and improving oil-water separation efficiency. These findings demonstrate the importance of optimizing operating flow conditions for the design of energy-efficient and scalable quartz-based filtration systems.

Table 5. Predicted Oil-Water Separation Efficiency under Different Inlet Velocity Conditions

Inlet Velocity (m/s)	Outlet Oil Fraction	Predicted Separation Efficiency (%)
0.001	0.02	98
0.002	0.04	96
0.003	0.06	94
0.004	0.08	92

Table 6. Quantitative Hydrodynamic and Separation Performance under Different Inlet Velocity Conditions

Inlet Velocity (m/s)	Average Velocity in Porous Zone (m/s)	Pressure Drop (kPa)	Outlet Oil Fraction	Separation Efficiency (%)
0.001	0.0035	5.0	0.02	98
0.002	0.0036	7.0	0.04	96
0.003	0.0037	9.0	0.06	94
0.004	0.0038	12.0	0.08	92

3.4.2. Sensitivity Analysis under Different Operating Conditions

To further evaluate the influence of operating conditions on filtration performance, a sensitivity analysis was conducted by varying the inlet velocity from 0.001 m/s to 0.004 m/s. The resulting pressure-drop behaviour and oil-water separation efficiency are illustrated in Figs. 7 and 8. As shown in Fig. 7, the pressure drop increased progressively from approximately 5 kPa to 12 kPa with increasing inlet velocity. This trend is expected because higher flow rates increase hydraulic resistance within the porous quartz filtration bed, resulting in greater energy dissipation during fluid transport. The approximately linear increase in pressure drop demonstrates stable porous-media flow behaviour and confirms that the filtration system operates within a low-pressure regime suitable for energy-efficient wastewater treatment applications.

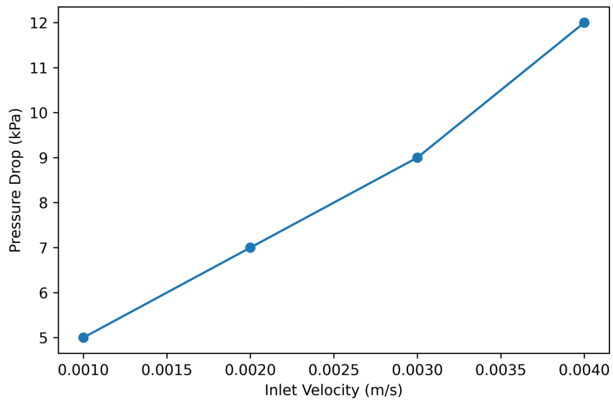

Fig. 7. Variation of pressure drop with inlet velocity for the surface-enhanced quartz granular filtration system.

Fig. 8 illustrates the corresponding variation in separation efficiency under different operating conditions. The predicted oil-water separation efficiency decreased from 98% at an inlet velocity of 0.001 m/s to 92% at 0.004 m/s. This reduction can be attributed to decreased residence time within the porous filtration zone. At lower velocities, oil droplets remain in contact with the hydrophilic quartz surface for longer periods, promoting enhanced fluid-surface interaction and improved oil retention. Conversely, higher velocities accelerate droplet transport through preferential flow paths and reduce the probability of droplet capture.

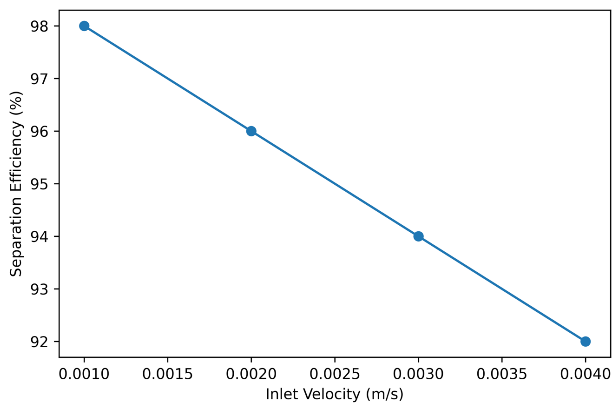

Fig. 8. Influence of inlet velocity on predicted oil-water separation efficiency.

The combined trends presented in Figs. 7 and 8 clearly demonstrate the trade-off between hydraulic throughput and separation performance. While increasing flow velocity improves processing capacity, it simultaneously increases pressure losses and reduces oil-removal efficiency. These findings confirm that operating conditions play a critical role in determining the hydrodynamic behaviour and separation effectiveness of surface-enhanced quartz filtration systems. From an engineering design perspective, the results suggest that inlet velocities in the range of 0.001-0.002 m/s provide the most favourable balance between pressure requirements and oil-water separation performance. The sensitivity analysis therefore provides quantitative guidance for the optimization and scale-up of quartz-based granular filtration technologies for industrial wastewater treatment.

3.4.3. Comparison with Previous CFD Studies and Scientific Contribution

Several computational fluid dynamics (CFD) investigations have been reported for oil-water separation systems, particularly membrane-based filtration units, ceramic membrane modules, and porous media separation devices. Previous studies primarily focused on evaluating flow distribution, pressure drop behavior, membrane fouling characteristics, and multiphase transport phenomena within conventional filtration systems. For example, Hosseini et al.[19] reported CFD modelling of pilot-scale membrane filtration systems and demonstrated that flow hydrodynamics strongly influence oily wastewater treatment efficiency. Similarly, Neto et al.[20] investigated multiphase flow behavior in tubular ceramic membrane modules and highlighted the importance of pressure distribution and phase transport in determining separation performance. These studies provided valuable insight into fluid transport mechanisms and membrane filtration performance; however, they primarily considered conventional filtration materials and did not explicitly investigate the influence of surface-engineered quartz granular media on oil-water separation behavior.

Furthermore, most previously reported CFD studies assumed constant porous-media properties and focused mainly on hydrodynamic characterization without establishing a direct relationship between experimentally measured wettability characteristics and multiphase separation performance. As a result, the combined effects of surface modification, wettability enhancement, porous-media hydrodynamics, and oil-water separation efficiency remain insufficiently understood. The present study advances existing knowledge by integrating experimentally validated wettability enhancement data obtained from hydrophilic nanoparticle-coated quartz particles into a porous-media CFD framework. Experimental characterization demonstrated a substantial reduction in contact angle from approximately 38° for raw quartz to ≤10° following hydrophilic nanoparticle coating, indicating significantly enhanced water affinity and reduced oil adhesion. Unlike previous CFD investigations that focused primarily on conventional membrane systems, the present work evaluates how surface-engineered quartz influences fluid-surface interaction, velocity distribution, pressure behavior, oil transport, and overall separation efficiency within a granular filtration system.

The CFD results, interpreted together with experimentally validated wettability measurements, indicate that enhanced hydrophilicity is associated with improved fluid-surface interaction, progressive reduction in oil volume fraction, and separation efficiencies ranging from 92-98%. The observed separation behavior is consistent with the experimentally measured reduction in contact angle and enhanced water affinity of the surface-modified quartz particles. The model further revealed the influence of inlet velocity on pressure-drop behavior and separation performance, providing quantitative guidance for optimization of operating conditions. These findings extend beyond conventional hydrodynamic analysis by establishing a direct relationship between surface engineering and oil-water separation behavior in porous quartz filtration systems.

Therefore, the principal scientific contributions of this work are: (i) development of a porous-media CFD framework for evaluating oil-water separation within surface-enhanced quartz granular filtration systems; (ii) integration of experimentally validated wettability characteristics of hydrophilic nanoparticle-coated quartz particles into the interpretation of multiphase transport behavior; (iii) quantitative evaluation of the relationship between inlet velocity, pressure drop, residence time, and oil-water separation efficiency; and (iv) demonstration of the potential of surface-engineered quartz as a low-cost, scalable, and energy-efficient alternative to conventional membrane-based separation technologies. Collectively, these contributions advance current understanding of the coupled effects of porous-media hydrodynamics, surface modification, and phase transport behavior in granular oil-water filtration systems and provide a foundation for future design and optimization of sustainable wastewater treatment technologies.

3.4.4. Comparison with Conventional Membrane Technologies

Conventional membrane technologies, including polymeric membranes, ceramic membranes, and nanostructured composite membranes, have demonstrated excellent oil-water separation performance, often exceeding 95% removal efficiency [39, 40]. However, these systems commonly experience membrane fouling, high fabrication costs,

Table 7. Comparison of the Present CFD Study with Previous CFD Investigations

Study	Separation System	CFD Focus	Key Findings	Advancement of Present Study
Hosseini et al.[19]	Membrane filtration	Hydrodynamics and scale-up	Flow behavior influences treatment efficiency	Incorporates surface-engineered quartz porous media
Neto et al.[20]	Ceramic membrane module	Multiphase flow behavior	Pressure and phase distribution affect separation	Includes wettability-enhanced granular filtration
Umar et al.[21]	Membrane channel design	Fouling control and flow characteristics	Improved channel geometry reduces fouling	Focuses on surface modification effects and porous media interaction
Present Study	Surface-enhanced quartz granular filtration	Hydrodynamics, porous-media flow, wettability interpretation, and separation performance	Predicted separation efficiencies of 92-98% under low-pressure operating conditions and identified the influence of inlet velocity on pressure drop and phase transport behavior	First CFD investigation combining experimentally validated hydrophilic nanoparticle-coated quartz wettability characteristics with porous-media flow modelling to evaluate oil-water separation performance in quartz granular filtration systems

limited chemical resistance, and increased operating pressure requirements, which may restrict their long-term industrial application [41]. In contrast, the present surface-enhanced quartz filtration system employs inexpensive naturally available quartz particles modified through hydrophilic surface engineering, providing a low-cost alternative for oily wastewater treatment.

The CFD simulations demonstrated that the modified quartz bed promotes gradual pressure reduction, stable porous-media flow, and progressive oil removal throughout the filtration depth. Unlike pressure-driven membrane filtration, the granular quartz system relies primarily on enhanced fluid-surface interaction within the porous medium, thereby reducing the likelihood of severe fouling while maintaining efficient separation. Furthermore, the relatively low operating pressure predicted by the CFD model suggests reduced energy consumption compared with many conventional membrane processes.

Although membrane systems generally provide superior selectivity for very fine emulsified droplets, surface-enhanced quartz filtration offers advantages in terms of operational simplicity, scalability, lower capital cost, and easier maintenance. Consequently, the proposed filtration strategy represents a promising complementary technology for industrial wastewater treatment, particularly where robust operation and economic feasibility are primary considerations.

3.5. Comparative Performance Analysis

Table 8 presents a comparative evaluation of the quartz granular filtration system against commonly reported oil-water separation technologies.

As shown in Table 8, although advanced technologies achieve very high efficiencies (>99%), they are associated with high complexity, cost, and fouling susceptibility. In contrast, the quartz-based system provides competitive performance (92-98%) while maintaining low cost, reduced fouling, and high scalability [42]. This makes the proposed system a practical and sustainable solution for industrial wastewater treatment.

3.6. Summary of CFD Simulation Observations

To further synthesize the results, the key hydrodynamic and separation behaviors are summarized in Table 9.

Table 9 highlights the relationship between hydrodynamic conditions and separation performance. The results confirm that improved wettability and controlled flow conditions significantly enhance oil removal efficiency.

The CFD analysis provides a comprehensive understanding of the internal mechanisms governing oil-water separation. The results confirm that separation efficiency is strongly influenced by the interaction between flow dynamics, porous media characteristics, and surface modification.

Table 8. Comparison of Quartz Granular Filtration with Advanced Oil-Water Separation Technologies

Technology Type	Separation Efficiency (%)	Complexity Level	Cost	Fouling Tendency	Scalability
Membrane Filtration	>99	High	High	High	Moderate
MOF-Based Materials	>99	Very High	Very High	Moderate	Limited
Hydrogel-Based Systems	90-99	High	Moderate	Moderate	Moderate
Conventional Filtration	40-80	Low	Low	Low	High
Quartz (This Study)	92-98	Low	Low	Low	High

Table 9. Summary of CFD Simulation Observations

Parameter	Observation	Impact on Separation
Velocity Distribution	Non-uniform with localized high flow regions	Reduced residence time in high-velocity zones
Pressure Profile	Gradual decrease along bed height	Indicates energy-efficient operation
Oil Volume Fraction	Decreases along flow direction	Confirms progressive oil removal
Flow Behaviour	Presence of preferential flow paths	Potential for channeling effects
Surface Enhancement	Improved flow- surface interaction	Enhances separation efficiency

The findings demonstrate that optimizing velocity distribution and minimizing flow channelling are critical for improving system performance. Furthermore, the integration of surface-enhanced quartz significantly improves phase interaction, leading to enhanced oil removal. Despite the promising results, certain limitations exist, including the assumption of homogeneous porous media and laminar flow conditions. Future work should incorporate turbulence effects, droplet dynamics, and experimental validation to improve model accuracy.

4. Conclusions

This study employed computational fluid dynamics (CFD) to investigate hydrodynamic behaviour and oil-water separation in surface-enhanced quartz granular filtration systems. The results demonstrate that non-uniform velocity distribution significantly influences separation performance, where reduced velocities enhance residence time and fluid-surface interaction, thereby improving oil removal, while high-velocity regions limit efficiency. The progressive pressure drop observed along the filtration bed confirms stable and energy-efficient porous media flow behaviour. In addition, the reduction in oil volume fraction along the flow path verifies effective phase separation within the system. Importantly, surface-enhanced quartz was shown to improve flow-surface interaction, leading to enhanced oil displacement and separation efficiency. The CFD model predicted separation efficiencies of up to 98%, which are consistent with experimentally reported trends for hydrophilic granular filtration systems. While maintaining low cost, low fouling tendency, and high scalability, positioning it as a practical alternative for industrial oily wastewater treatment.

This study developed a CFD framework for analysing hydrodynamic behaviour and oil-water separation within a surface-enhanced quartz granular filtration system. The simulations demonstrated that velocity distribution, pressure gradients, and multiphase transport collectively govern separation performance. Lower inlet velocities promoted increased residence time and improved interaction between the water phase and hydrophilic quartz surfaces, resulting in higher predicted oil removal efficiency. The numerical predictions, interpreted together with experimentally validated wettability characteristics, indicate that surface modification significantly enhances fluid-surface interaction and promotes progressive oil removal throughout the porous filtration bed.

From an engineering perspective, the proposed CFD framework provides a valuable design tool for optimizing porous-media filtration systems while minimizing experimental cost and development time. The low predicted pressure losses indicate potential energy-efficient operation, suggesting that surface-enhanced quartz filtration may provide a cost-effective alternative or complementary technology to conventional membrane systems for industrial oily wastewater treatment.

Nevertheless, the present study represents a simplified numerical model based on homogeneous porous media, steady-state laminar flow, and literature-supported validation rather than direct one-to-one experimental verification. Consequently, the predicted separation efficiencies should be interpreted as numerical predictions consistent with experimental trends rather than direct experimental measurements. Future work should incorporate transient flow behaviour, heterogeneous porous structures, droplet population balance modelling, and simultaneous laboratory validation under identical operating conditions to further improve predictive capability and industrial applicability.

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