

# A Review of Fluid Animation Simulation in CG

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## Abstract

Fluid simulation stands as a cornerstone technology in modern computer graphics, underpinning advancements in film and television production, interactive game development, and immersive virtual reality (VR) experiences. Its core mission is to digitally replicate the intricate natural motions of fluids—including liquids, gases, and their interactions—while striking a critical balance between computational efficiency, high visual realism, and artistic controllability. Propelled by rapid developments in parallel computing hardware and artificial intelligence algorithms, fluid simulation has evolved into three dominant technical paradigms: data-driven methods, physics-based methods, and hybrid approaches that merge the strengths of the first two. This review comprehensively synthesizes key research findings from domestic and international scholars across these paradigms, delving into progress in method optimization, scenario-specific applications, and technical evaluation systems. It systematically summarizes the unique strengths and inherent limitations of each approach, dissects pressing current challenges such as poor cross-scene generalization, excessive computational costs, and inadequate adaptation to extreme scenarios, and outlines prospective future research directions. By doing so, this review aims to provide a valuable theoretical and practical reference for researchers and practitioners in related fields.

## Keywords

Fluid Simulation; Data-Driven Methods; Physics-Based Methods; Hybrid Simulation; Computer Graphics

## 1. Introduction

Fluid simulation has become an indispensable technical pillar in the realm of computer graphics, with far-reaching applications spanning high-fidelity film special effects, dynamic game environments, and immersive VR interactions. Its fundamental objective is to digitally reconstruct the natural motion laws of fluids—such as the flow of water, the diffusion of smoke, and the interaction between different fluid phases—while satisfying three core requirements: efficient computation (to enable real-time or near-real-time applications), realistic visual presentation (to deceive human perception), and flexible controllability (to meet artistic or functional demands).

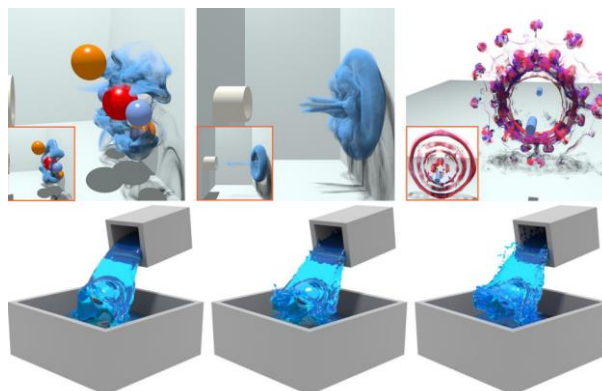
Over the past decade, driven by the exponential growth of computing power (e.g., GPU parallel computing capabilities) and the rise of machine learning technologies, fluid simulation methods have undergone significant evolution, gradually forming three distinct technical systems. Data-driven methods leverage large-scale datasets and neural network models to achieve fast fluid motion prediction and editing; physics-based methods rely on the numerical solution of fundamental fluid mechanics equations (e.g., Navier-Stokes equations) to ensure physical authenticity; hybrid methods, as an emerging hotspot, integrate the efficiency of

data-driven approaches with the accuracy of physics-based methods to overcome the limitations of single-paradigm solutions.

This review is based on a systematic collation of domestic and international literature, aiming to provide a panoramic overview of the current state of fluid simulation research. It is structured around five key dimensions: data-driven methods, physics-based methods, hybrid physics-data driven methods, specific application scenarios, and technical reviews/evaluations. By analyzing the progress, strengths, and limitations of each dimension, this review identifies critical research gaps and proposes future development directions, thereby offering insightful guidance for subsequent studies in the field.

## 2. Data-driven method

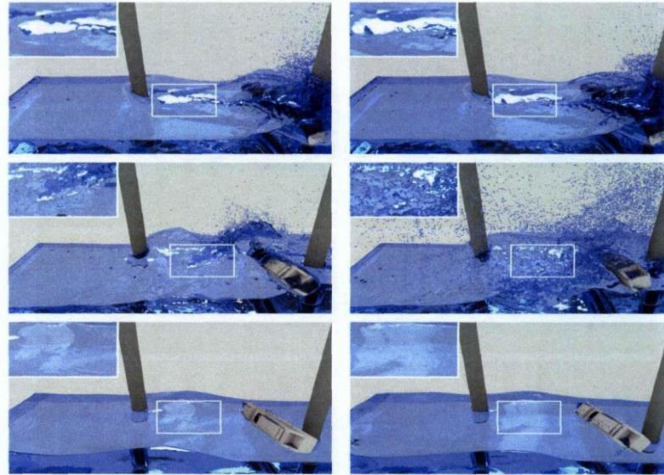
Deng, 2021 shows that the special effects simulation method combined with fluid equation and deep neural network can improve the accuracy of spatial reconstruction, reduce tracking errors and accelerate large-scene simulation. [1] Peng Chen, 2022 proposed multi-scale explainable basis decomposition, random forest distance water splash detail enhancement, and CNN water surface wave super-resolution methods to achieve efficient and controllable generation of high-resolution fluid animations, balancing physical accuracy and editing flexibility. [2] Kang et al., 2022 proposed a modeling method based on fluid animation graphs, which generates animation graphs through frame similarity and responds to user input, realizing real-time simulation and natural transitions, but relying on pre-generated sequences leads to a decrease in complex input accuracy (Figure 1). [3] Mahapatra et al., 2022 proposed a two-stage static image fluid animation method that optimizes the flow field through user motion prompts and GANs, with better generalization than the baseline model, but only for fluid elements. [4] Kim et al., 2020 proposed Lagrangian 3D fluid neural style transfer technology, which greatly shortens the computation time and enhances the ability of art control, but the large-scale simulation performance is not good. [5] Chen et al., 2021 reviewed data-driven fluid simulation and pointed out its efficiency advantages and insufficient interpretability. [6]



**Fig. 1** Various data-driven fluid simulation methods for *Phoxinus phoxinus* subsp. *phoxinus* effects[2].

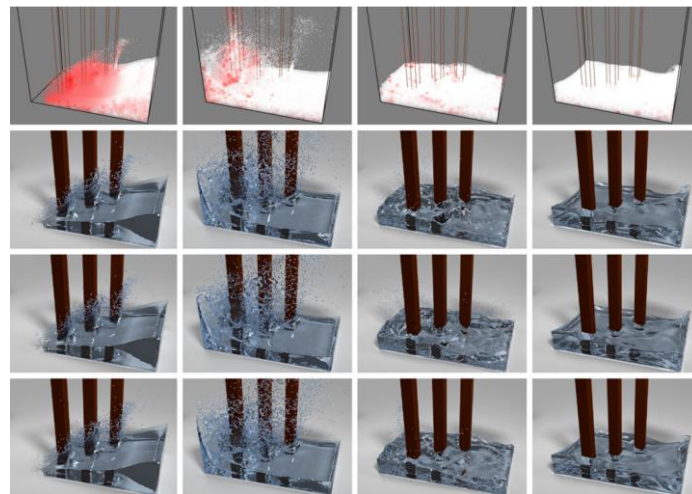
## 3. Physics drive method

Liu Sinuo, 2021 proposed Rankine vortex correction, vortex refinement, and gas-liquid coupling model to improve the realism of turbulence and foam effects, but the parameters need to be precisely controlled and the adaptability to extreme scenarios is insufficient [7]. (Figure 2)



**Fig. 2** Coupling Experiment of Sea Waves and Ships[7].

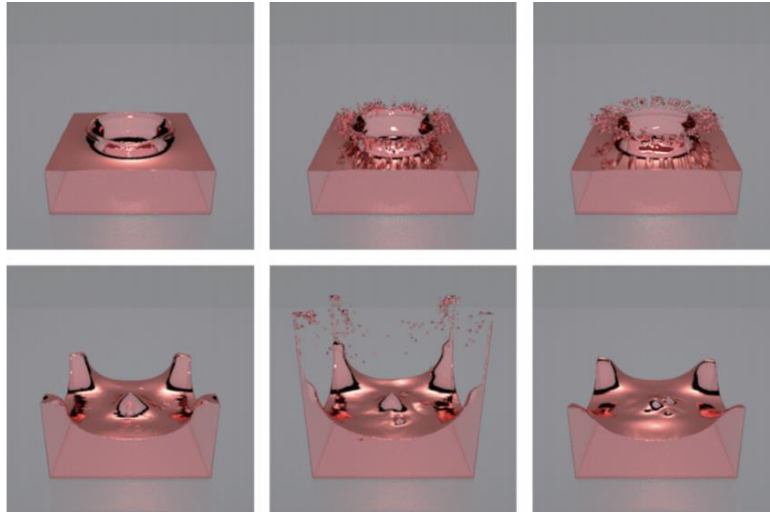
Shao Xuqiang et al., 2021 proposed a stable SPH-SWE model, which combines GPU parallel and screen-space rendering to improve the problem of terrain particle accumulation, but CPU-GPU data exchange limits efficiency. [6] Ban et al., 2018 proposed an adaptive step SPH method to allocate time steps according to the local state of particles to improve the efficiency of high dynamic scenes, but there is a slight momentum non-conservation error [8] (Figure 3)



**Fig. 3** Breaking dam with obstacles simulated using presented method ( $t \frac{1}{4}$  1.2 s, 2.0 s, 4.0 s and 4.84 s).

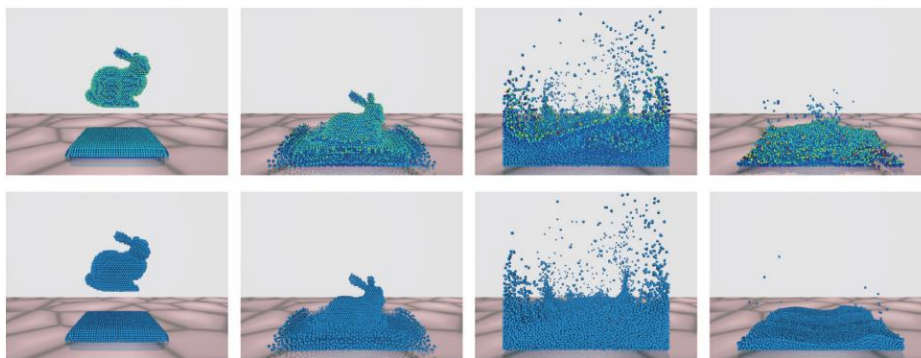
Top Particles colored according to individual step (red for small dts and white for large dts). Second row corresponding frames. Third row corresponding frames simulated using globally adaptive stepping method. Bottom corresponding frames simulated using basic WSPH[8].

Judice et al., 2020 proposed a 2D fluid animation method that combines sketches, diffusion reactions, and LBMs to achieve intuitive control, but it is limited to 2D and has high computational costs. [9] Zhang et al., 2020 proposed a GPU-accelerated mesh-particle coupling method to improve interface tracking accuracy through second-order distribution function reconstruction, but it is only suitable for low-speed scenarios. [10] Lyu et al., 2021 proposed a narrowband multiphase flow method to reduce noise through weighted coupling velocity transmission, but did not solve the problem of multiphase current expansion [11] (Figure 4)



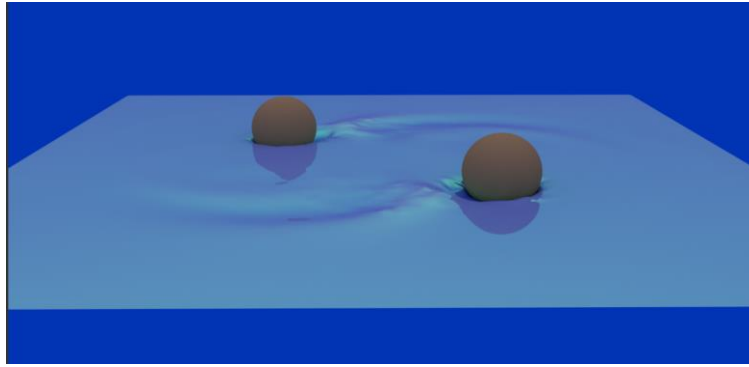
**Fig. 4** A droplet dropping into a pool creating crown splashes with an effective resolution of 1283 . From left to right: The same frame simulated using NB-MultiPIC, NB-MultiFLIP, and NB-MultiAPIC, respectively. MultiPIC restrains the motion of the liquid and cannot form a complete crown. NB-MultiAPIC forms a complete crown. Although NB-MultiFLIP also forms a complete crown, NB-MultiFLIP suffers from additional noise.[11]

Zeng et al., 2021 proposed an adaptive smooth-length SPH method based on neighborhood particle density weighting to improve interpolation accuracy, but the neighborhood search efficiency is low [12] (Figure 5)



**Fig. 5** Bunny-shaped fluid falling into a water tank (top: ASLSPH; bottom: DFSPH).[12]

Yang et al., 2021 introduced Helmholtz decomposition into SPH and proposed a velocity projection scheme that is more efficient than existing methods but cannot simulate vortex effects.[13] Cen et al., 2025 proposed a hierarchical 3D fluid simulation method with a spherical coordinate system to achieve efficient simulation, but there are slight artifacts in the polar regions. [14] Limtrakul et al., 2020 proposed an SPH method for Reeb diagram skeleton particles versus adaptive kernel density estimation, preserving low-density region detail but inefficient large-density regions. [15] Hardt et al., 2019 proposed a consistent Shepard interpolation technique that reduces density noise but introduces 20% computational overhead. [16] Probst et al., 2023 proposed an integral SPH fluid-rigid body coupling method that accurately simulates static friction, but with high particle demand and reference serial numbers in order of reference. [17] Todd, 2017 Fluid animation surface modeling by vortex dynamics and integral equations improves efficiency, but the complex topology adaptability is poor and meets the requirements of reference priority [18] (Figure 6)



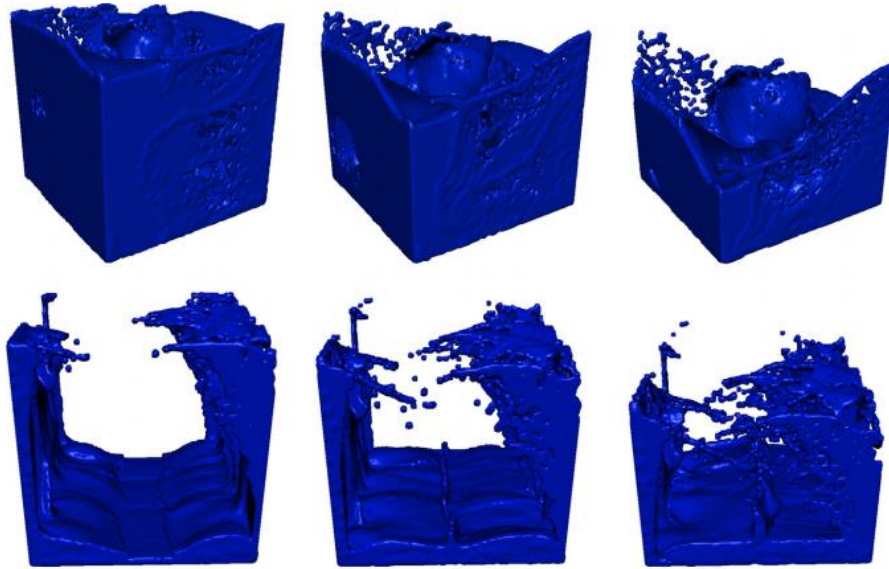
**Fig. 6** Movingballswithwake.[18]

Probst et al., 2025 propose an SPH solver that unifies pressure, surface tension, and friction to simulate small-scale droplet behavior, but the computational intensity is increased [19] (Figure 7)



**Fig. 7** Rain on the Lucy statue. At first, our friction and surface tension formulation together allow droplets to stick to the statue. Only after the droplets grow larger do they start rolling downwards, leaving wet trails behind them. The trails mark preferred paths downwards for other droplets due to less frictional resistance, causing the formation of small fluid streams. Over ten million fluid particles of size 1 mm were used to simulate the rainwater. The Lucy statue stems from the Stanford 3D Scanning Repository; we use a version modified by Melllla.[19]

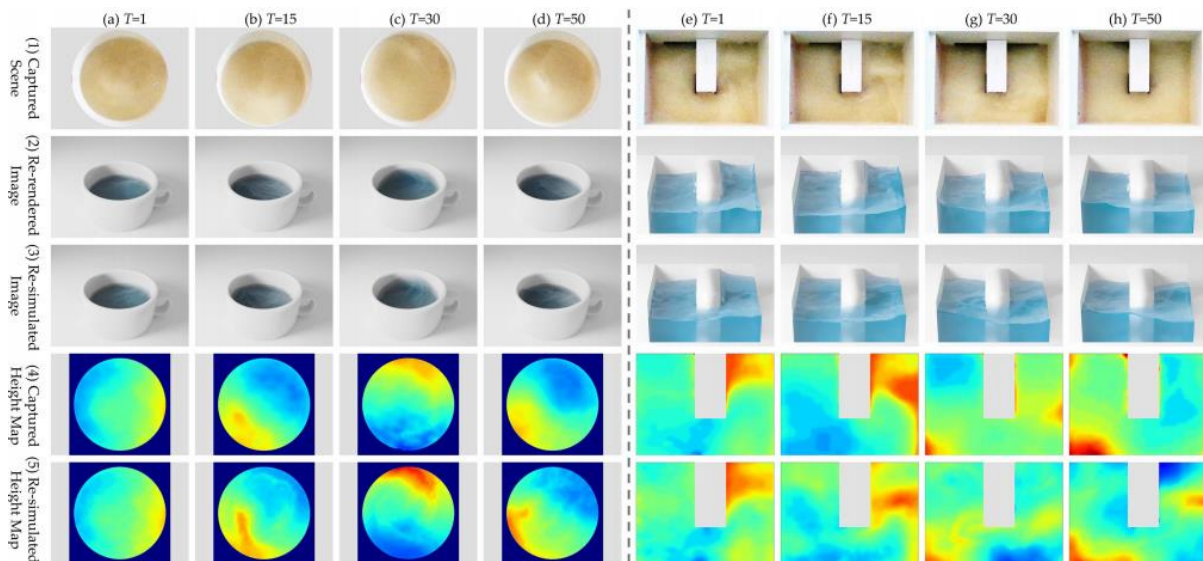
Andersen et al., 2017 proposed a GPU parallel LCP solver to accelerate fluid simulation, but the accuracy of large meshes decreases. [20] (Figure 8) Carensac et al., 2023 Study GPU Prediction - Corrected Particle Fluid Simulation Optimization, Found Hardware-Specific Optimization Effects with Cyclic Instability. [21] Wang et al., 2023 (Xiaokun Wang et al.) proposed an incompressible numerical density SPH method to stabilize the simulated liquid-elastic coupling but could not handle the high-density ratio. [22] Liu et al., 2023 (Sinuo Liu et al.) proposed a dynamic hierarchical adaptive SPH method (FluidPlaying) to achieve 3-fold acceleration but requires temporal adaptation. [23] Pan et al., 2015 reviewed vortex-based fluid animation methods and pointed out their turbulence simulation advantages but could not add new vortices. [24] Wu, 2021 shows the progress of fluid-solid simulation through related papers, covering a wide range but not deeply analyzing the limitations. [25] Akhunov et al., 2023 evaluated SPH boundary processing methods, designed standardized experiments, provided comparison benchmarks, but focused only on particle-based methods. [26] Wang Xiaokun et al., 2024 Review of Ten Years of Physics Driven Fluid Simulation, Classification System, but Lack of Implementation Details. [27] Ban et al. present an adaptively stepped SPH method for fluid animation via asynchronous time integration, which saves computational time by allocating resources to complex regions. [28]



**Fig. 8** Top: Frames 80, 90 and 100 of our 1003 scenes using the proposed minimum map Newton method. Bottom: Frames 140, 150 and 160 for another 1003 scenes. See supplementary video for both scenes.[20].

#### 4. Mixed Theory - Data-Driven Approach

Xiao Xiangyun et al. 2020 review pointed out that the physics-driven method can improve efficiency through projection step acceleration, but it is easy to lose accuracy. Data-driven approaches can be accelerated, but physical consistency is insufficient. [29] Zhang Yalan, 2020 proposed a prediction-correction acceleration algorithm and FluidsNet to achieve large-scene simulation of non-Newtonian fluids, but boundary processing does not cover multiphase interactions. [30] Xie et al., 2025 proposes a volumetric modeling framework that integrates deep learning and physical simulation to estimate parameters in real time, but is limited by static obstacles [31] (Figure 9)



**Fig. 9** Re-simulated results of real-world scenes. (a)–(d) Circular scenes with rotational wave motions. (e–h) Rectangular scenes with obstacles. (1) The captured real images. (2) The re-rendered images. (3) Our re-simulated images. (4)–(5) Their corresponding height maps.[31]

## 5. Specific application scenarios

Zhang et al., 2020 proposed a multi-GPU cluster PBF simulation tool to optimize the real-time performance of VR fluids, but the rendering of complex scenes is insufficient. [32] Wang Yue et al., 2024 propose a VR foveal fluid simulation method to divide high/low resolution regions to achieve 2.27x acceleration but with edge bumps. [33] Feng et al., 2019 proposed a depth camera fluid reconstruction method combined with wave-particle systems to simulate solid-liquid interactions, but only for altitude fields. [34] Kim discloses a system and method for fluid rendering in cartoon animation, using mesh modeling, raytracing, Phong illumination model, silhouette extraction and non-photorealistic rendering to achieve cartoon-style fluid visualization. [35]

## 6. Other technical methods

Feng Xiaobing et al., 2020 proposed a fluid reconstruction method for depth map sequences, which optimizes the velocity field in combination with physical constraints, but the distortion caused by the lack of edges in multiple frames. [36] Peng et al., 2023 Combine ant colony algorithm with orthogonal design to optimize fluid simulation stability, but canstability butprediction error. [37] Gowthaman et al., 2022 proposed a goal-driven approach to the fusion of time reversal and simulation to achieve natural fluid shape, but lacks sourceshape butysical interaction. [38] (Figure 10) Yang GAO et al., 2025 proposed an implicit particle interpolation lattice Boltzmann method to reduce time consumption through parallel calculation, but the stability of extreme scenarios is not clear. [39] Stomakhin et al., 2023 proposed a layered fluid volume modeling method to improve the efficiency of interactive simulation, but the layer thickness trade-off affects the accuracy. [40]



**Fig. 10** Frames from art-directed fluid simulation. A target simulation (green) combines with the source simulation (blue); the target simulation forms the target shape, while the source simulation provides surrounding fluid motion.[38].

## 7. Discussion

Fluid simulation has matured into a sophisticated field with three core technical systems—data-driven, physics-based, and hybrid methods—each with distinct strengths and application niches.

Data-driven methods have achieved significant advancements in efficient simulation and stylized editing through machine learning. Domestic research has pushed forward in accuracy optimization and editing flexibility, while international work has excelled in controllable animation generation and artistic style transfer. However, critical challenges remain, including poor cross-scene generalization, risks to physical fidelity, and heavy reliance on large datasets.

Physics-based methods continue to ensure high physical authenticity through numerical solutions of fluid mechanics equations. Domestic progress in gas-liquid coupling and terrain-adaptive SPH-SWE models has enhanced detail restoration, while foreign innovations in

adaptive time stepping and monolithic SPH coupling have improved stability and efficiency. Yet, breakthroughs are still needed in computational efficiency for large-scale scenes and adaptation to extreme dynamic scenarios.

Hybrid methods have emerged as a powerful approach to balance efficiency and authenticity. Domestic research on non-Newtonian fluid simulation and physics-informed parameter inversion has demonstrated their potential, alongside foreign work on numerical optimization and layered interface simulation. Nonetheless, issues such as time-dependent error accumulation and limited scene adaptability require further research.

In application-specific domains, domestic advancements in VR multi-GPU simulation and depth-based reconstruction have addressed real-time and sensing challenges, while foreign innovations in foveated rendering and target-driven animation have optimized user experience and artistic control. These methods, however, often lack robust handling of complex, dynamic scenes with multiple interacting elements. (Table 1)

**Table 1.** Five categories comparing

Category	Example	Merit	Flaw
Data-driven method	<b>Research on Data - Driven Fluid Animation Editing and Detail Enhancement Methods</b>	<ol style="list-style-type: none"> <li>1. Addressing time-consuming traditional fluid simulation &amp; poor interpretability of deep learning models</li> <li>2. Proposed four targeted data-driven methods</li> <li>3. Supported by sufficient experimental verification</li> </ol>	<ol style="list-style-type: none"> <li>1. Method's generalization ability limited to incompressible fluids</li> <li>2. Lack of a unified framework</li> <li>3. Adaptability to real complex scenarios needing improvement</li> </ol>
	<b>Controllable Animation of Fluid Elements in Still Images</b>	<ol style="list-style-type: none"> <li>1. Proposed two-stage flow field estimation method</li> <li>2. Quantitative &amp; qualitative performance superior to the baseline</li> <li>3. Generalization to motion directions outside the training set</li> </ol>	<ol style="list-style-type: none"> <li>1. Applicable only to fluid elements</li> <li>2. Cannot model rigid object movement</li> <li>3. Cannot model movement of adjacent different flow fields</li> </ol>
Physics drive method	<b>Physics-Based Detail Enhancement and Gas-Liquid Coupling Simulation for Fluid Animation</b>	<ol style="list-style-type: none"> <li>1. Proposed corresponding algorithms for fluid animation issues</li> <li>2. Experiments verified algorithm effectiveness</li> <li>3. Enhanced fluid animation realism</li> <li>4. Improved simulation efficiency</li> </ol>	<ol style="list-style-type: none"> <li>1. Insufficient elaboration on adaptability in ultra-complex multi-physics field scenarios</li> <li>2. Lack of comparison with new AI fluid simulation methods</li> </ol>
	<b>Unified Pressure, Surface Tension and Friction for SPH Fluids</b>	<ol style="list-style-type: none"> <li>1. Unified SPH fluid solver</li> <li>2. Accurate simulation of real phenomena</li> <li>3. Consistent force calculations</li> </ol>	<ol style="list-style-type: none"> <li>1. Surface tension requiring larger kernel support</li> <li>2. Friction not distinguishing between static and dynamic friction</li> <li>3. Limited time step when simulating high-speed small particles</li> </ol>
Mixed Theory - Data-Driven Approach	<b>Research on Physics-Based and Data-Driven Fluid Animation</b>	<ol style="list-style-type: none"> <li>1. Comprehensive review of physics-driven &amp; data-driven fluid animation methods</li> <li>2. Clear classification of fluid animation methods</li> <li>3. Analysis of key issues &amp; trends in fluid animation</li> <li>4. Reference value in the fluid animation field</li> </ol>	<ol style="list-style-type: none"> <li>1. Insufficient coverage of practical operation details or latest progress in some methods</li> <li>2. Unthoroughly addressed issues of data-driven accuracy and universality</li> </ol>
	<b>Fluid Inverse Volumetric Modeling and Applications From Surface Motion</b>	<ol style="list-style-type: none"> <li>1. Integrate deep learning with physical simulation</li> <li>2. Achieving inverse modeling from fluid surface to volume</li> <li>3. Real-time parameter estimation</li> <li>4. Support for scene re-editing</li> </ol>	<ol style="list-style-type: none"> <li>1. Applicable only to simple scenarios</li> <li>2. Cumulative errors in long-term simulations</li> <li>3. Difficulty adapting to diverse spatiotemporal scales</li> </ol>
Specific application scenarios	<b>Foveated Fluid Animation in Virtual Reality</b>	<ol style="list-style-type: none"> <li>1. Multi-region adaptive fluid simulation</li> <li>2. Improves computational efficiency</li> <li>3. Maintains approximately high-resolution visual quality</li> <li>4. Validated via user research</li> <li>5. Explores FPPD metric</li> </ol>	<ol style="list-style-type: none"> <li>1. Slightly uneven edges of regions F and P</li> <li>2. FPPD not yet an ideal evaluation metric</li> <li>3. Damping effect of low-resolution basic simulations affecting vision</li> </ol>
	<b>Depth Camera Based Fluid Reconstruction and its Solid-fluid Interaction</b>	<ol style="list-style-type: none"> <li>1. Repair depth map &amp; enhance fluid details</li> <li>2. Achieve real-time solid-liquid interaction</li> <li>3. Balance efficiency and realism of fluid simulation</li> </ol>	<ol style="list-style-type: none"> <li>1. Representing fluids solely with height fields</li> <li>2. Cannot handle complex phenomena</li> <li>3. Data collection requiring fluid dyeing</li> <li>4. Limits applicable scenarios</li> </ol>
Other technical methods	<b>Time Reversal and Simulation Merging for Target-Driven Fluid Animation</b>	<ol style="list-style-type: none"> <li>1. Combine source simulation with forward &amp; reverse target simulation</li> <li>2. Achieve art-oriented fluid animation</li> <li>3. Not disrupt fluid natural movement</li> <li>4. Be compatible with existing particle simulators</li> <li>5. Have efficient computation</li> </ol>	<ol style="list-style-type: none"> <li>1. No physical interaction between source and target simulations</li> <li>2. Poor continuity of dynamic targets</li> <li>3. Particle spacing limits shape fidelity</li> <li>4. No support for pure grid simulators</li> </ol>
	<b>Method for Generating Simulations of Fluid Interfaces for Improved Animation of Fluid Interactions</b>	<ol style="list-style-type: none"> <li>1. Layered modeling of secondary materials</li> <li>2. Simplified calculation of boundary conditions</li> <li>3. Efficiently balance simulation realism and computational cost</li> <li>4. Support art-oriented adjustments</li> </ol>	<ol style="list-style-type: none"> <li>1. Weakly coupled scheme lacks realism in scenarios</li> <li>2. Some parameters depend on manual settings</li> </ol>

## 8. Conclusion

Future research should prioritize several directions: developing cross-scene generalization models with strong physical constraints to enhance adaptability; designing efficient numerical algorithms and hardware-accelerated architectures to reduce computational costs; Build a strongly coupled multiphysics framework to support complex phase transitions and multi-matter interactions; and advancing lightweight simulation technologies for edge devices and mobile applications. By addressing these areas, fluid simulation will continue to expand its applications, enabling more immersive, efficient, and realistic digital experiences.

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