Visualization and Visual Analysis for Multiphase Flow

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Introduction

When investigating multiphase flow, important aspects to consider are free surfaces, their influence on coherence and breakup of droplets, and the influence of droplet-local flow on droplet shape and topology. To this end, we want to provide visualization techniques and the means for visual analysis of complex multiphase flow data. This data is obtained from *direct numerical simulations* (DNS), in this case from the solver *Free Surface 3D* (FS3D) [1], which solves the Navier-Stokes equations for incompressible multiphase flow. The data consists of a velocity field and a *volume of fluid* (VOF) [2] field, whereas the latter can be used to reconstruct the fluid interface.
In the following, we will present three projects, which all aim at using visualization for gaining understanding of phenomena related to flow in droplets and forces acting on the free surfaces.

Visual Analysis of Interface Deformation

This project concerns itself with the investigation of the influence of forces acting on the surface of droplets. To this end, two derived quantities are used for visualization: interface stretching and interface bending. The former can be seen in Figure 1(a). Here, interface stretching is visualized using tube glyphs, their orientation indicating the direction of stretching, their color showing the magnitude. On the left side of the image, only the larger values indicating stretching are shown in red. Note the orientation of the glyphs along the tunnel-like structures, which depict that the fluid is moving from the tunnels into the larger structures at their ends. On the right side, the smaller values are visualized in blue, which indicate contraction. Here, the orientation of the glyphs allows the interpretation that the tunnel-like structures are subject to thinning and may eventually collapse. This outcome can be observed in the subsequent time steps shown in Figures 1(b) and (c). Hence, interface stretching enables us to analyze the effect of the surface tension force on coherence and breakup of droplets.

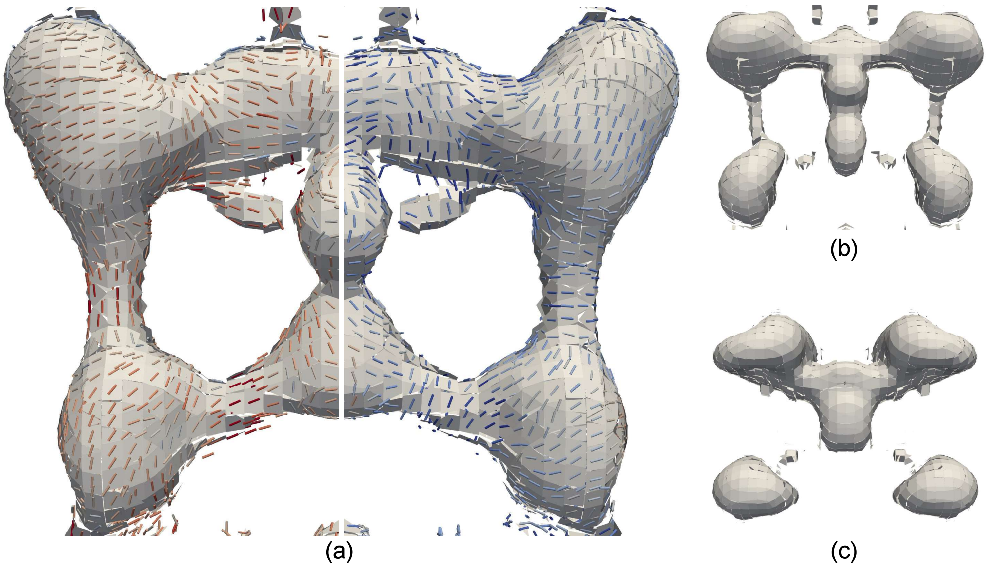


Figure 1. Interface stretching. For the symmetric dataset in (a), the larger values and corresponding vectors are shown in red, the smaller values are visualized indicating contraction in blue. Subsequent time steps are depicted in (b) and (c).

The second quantity, interface bending, is visualized in Figure 2 on a dataset where two droplets of different species are at the onset of coalescence. Due to the different fluid properties of the droplets, they exhibit a large surface tension gradient at the point where they are initially touching. This leads to forces induced by Marangoni convection, and fluid from the right droplet begins to spread across the surface of the left one, forming a capillary wave. Figures 2(a) to (d) show this evolution. Here, the largest bending of the surface is visualized, where the red glyphs show an increase in convexity in front of the wave and blue glyphs an increase in concavity in its wake. Thus, the visualization allows us to analyze the induced forces by means of interface bending.

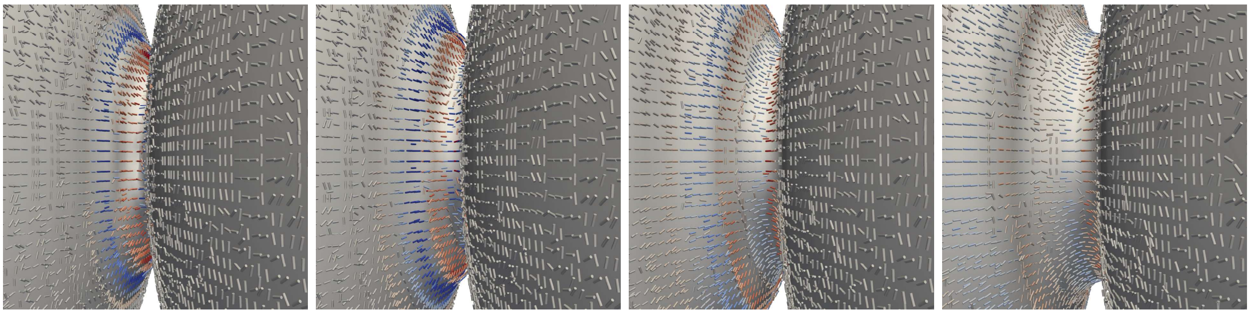
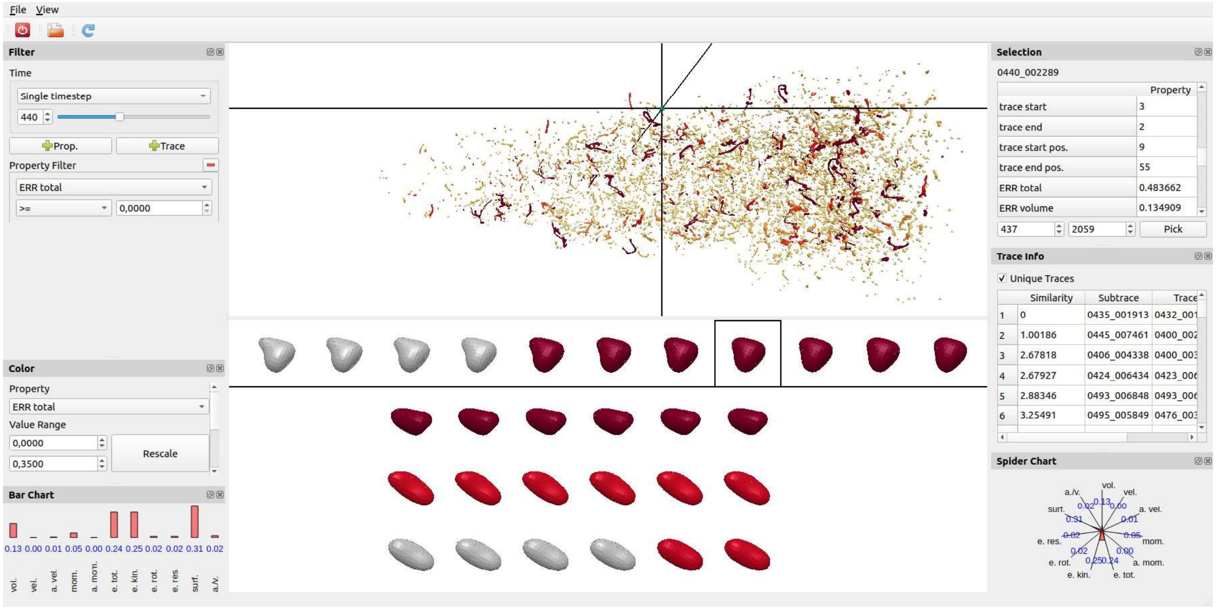

(a) (b) (c) (d)

Figure 2. Interface bending. The time steps from (a) to (d) show tube glyphs for an increase in concavity in red and an increase in convexity in blue, their orientation indicating the direction of change.

Visual Analysis of Irregular Droplet Behavior

To be able to understand complex phenomena and datasets, we aim at employing machine learning techniques together with visual analysis methods, in order to detect anomalous droplet behavior. For this, we compute per-droplet properties, such as average velocity, energies, and surface-to-volume ratio, use machine learning to train a very simple neural network, and finally visualize the prediction error for the input properties. A large prediction error means that the droplet exhibits unusual, non-standard behavior. This makes the droplet interesting for us to analyze. The whole process allows us then to visually analyze large, complex datasets, as seen in Figure 3 for a jet dataset.



Single timestep
440

Property Filter
ERR total
>= 0,0000

Color
Property
ERR total
Value Range
0,0000
0,3500

Selection
0440_002289

	Property
trace start	3
trace end	2
trace start pos.	9
trace end pos.	55
ERR total	0.483662
ERR volume	0.134909

437 2059

Trace Info
☑ Unique Traces

	Similarity	Subtrace	Trace
1	0	0435_001913	0432_001
2	1.00186	0445_007461	0400_002
3	2.67818	0406_004338	0400_003
4	2.67927	0424_006434	0423_006
5	2.88346	0493_006848	0493_006
6	3.25491	0495_005849	0476_003

Figure 3. Visual analytics framework. Filter options are available on the upper left side; information and droplet properties are visualized and shown on the lower left and on the right side. In the center, the dataset is shown in the top view, as well as droplets similar to the selected one in the bottom view.

For interactive analysis, the user can now filter for different prediction errors, droplet shapes and any of the input properties, as well as combinations thereof. After interactively selecting a droplet of interest in the main view, information about the droplet properties is shown as text and visualized in bar and spider charts. Additionally, other droplets with similar properties are drawn in the view below, showing the droplets at different time steps. This allows the user to find and compare droplets easily in a complex dataset. Other features include the visualization of time series, where multiple time steps are aggregated into one visualization, allowing the user to see the evolution of droplets.

Using our framework for visual analysis of the shown jet dataset, we ended up with some interesting findings. Droplets with low prediction error usually exhibited shear flow. However, in droplets with larger prediction error, we sometimes encountered vortices or saddles. Additionally, our framework lends itself well for debugging purposes, as large errors might also arise due to numerical issues or bugs in the solver code.

Visualization of Droplet-Local Flow

To investigate the influence of fluid dynamics on droplet behavior and topology, we want to employ streamlines, pathlines, and streaklines. The major problem with those techniques in three dimensions is visual clutter and occlusion. Especially when dealing with high translational or rotational velocities of droplets, this leads to non-expressive visualizations, as can be seen in Figure 4(a) for streamlines in a jet dataset. Aside from the general direction of the flow, we are unable to observe details. Using a droplet-local approach, as seen in Figure 4(b), this disadvantage can be mitigated, revealing much finer structures.

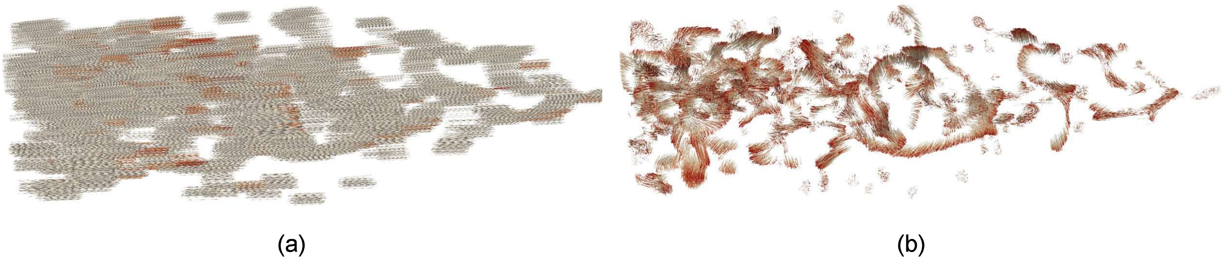


Figure 4. Streamline visualization for a jet dataset, with streamlines from the classic approach in (a), and droplet-local streamlines computed with our method in (b). Lines are colored from white to red to indicate the flow direction.

Hence, the idea is to remove the translational and rotational velocity parts from the velocity field, essentially using a different frame of reference per droplet. For a single droplet, this would mean that we observe it through a camera, which is moving with the same average velocity and rotating around the same axis as the droplet. Results can be seen in Figure 5 for pathlines in a drop collision dataset. For example, the droplet-local pathlines in Figure 5(b) strongly indicate that the fluid is gathering in the larger spherical structures at both ends, eventually leading to a breakup. This cannot be seen as easily in Figure 5(a) for the classic pathlines. Moreover, in Figure 5(d), showing the droplet-local approach, we can observe a saddle structure within the droplet at whose center we would expect a saddle point. This is not visible in Figure 5(c) visualizing classic pathlines.

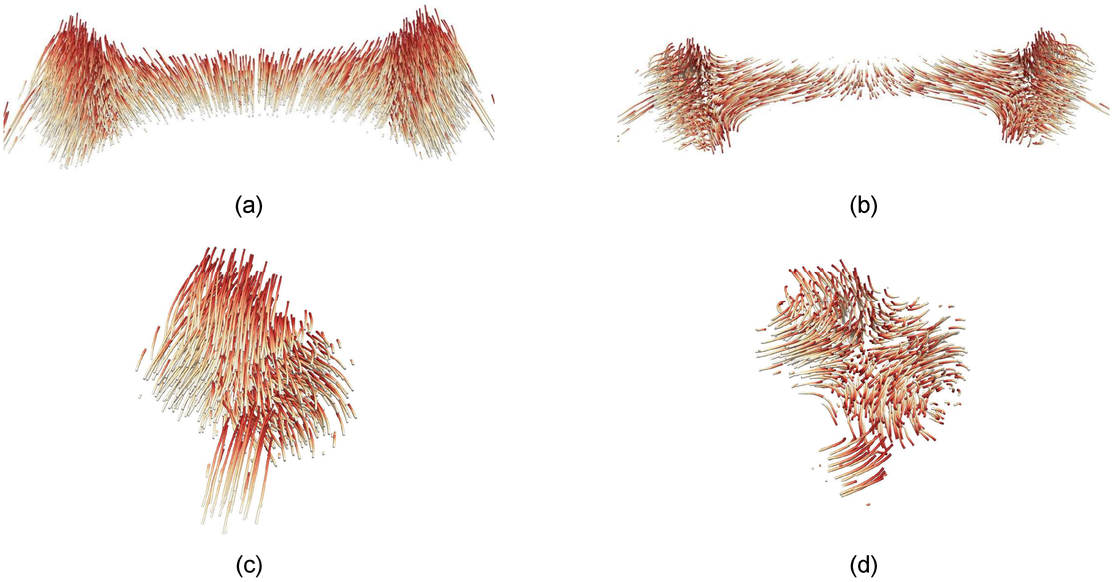


Figure 5. Pathline visualizations for a drop collision dataset containing many droplets. On the left side ((a) and (c)), classic pathlines are shown. On the right side ((b) and (d)), droplet-local pathlines are visualized for the same respective droplets.

Extending this work to support feature-local line integration methods, where the droplet's frame of reference is fixed relative to, e.g., a Lagrangian coherent structure, we want to investigate the influence of fluid dynamics in breakup regions.

References

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[2] Hirt C., Nichols B., Volume of fluid (VOF) method for the dynamics of free boundaries, in: Journal of Computational Physics 39, 1 (1981), 201–225.