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On 'Tears of Wine': Flow due to Solutocapillary Effect Formed on Inclined Wall

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Abstract: Phenomenon known as 'tears of wine' arises on an inclined plate partially submerged in a bulk of alcohol-water mixture. This phenomenon apparently exhibits a periodic ordered structure, the flow field itself evolves quite complex feature; especially in the vicinity of the tear. In the present study, the authors paid their special attention to this unique, complex flow field of O(1 mm) with deformable surface. The flow pattern and the spatio-temporal particle behavior in the tear were reconstructed by applying three-dimensional particle tracking velocimetry (3-D PTV).

Keyword: Tears of wine, solutocapillary effect, 3-D PTV.

1 Introduction

One can see a beautiful fluid dynamics in drinking wine in a glass. This phenomenon widely-known as 'tears of wine' (see Fig. 1) arises on an inclined plate partially submerged in a bulk of alcohol-water solution. More active evaporation of alcohol in a region of meniscus comparing to the bulk leads to concentration gradient between the meniscus and bulk regions. This results in a surface tension gradient along free surface of the fluid, which drives flow crawling up the plate against the gravity. The flow caused by surface tension gradient due to the gradient of the concentration is called solutocapillary-driven convection. Bumps are formed in the boundary region between the rising thin liquid film and falling liquid due to the gravity. The falling liquid on the plate evolves a kind of Rayleigh-Taylor instability, thus the bulges with a certain wavelength in a span-wise direction (the 'tears') emerge.

Although this phenomenon apparently exhibits a periodic ordered structure, the flow field itself evolves quite complex feature; especially in the vicinity of the tear. When the edge of the tear touches the surface of the bulk liquid in the reservoir, some portion of the liquid in the tear is sucked by the bulk, and then the tear rises back again due to the surface tension. There exists a theoretical and experimental research (Hosoi & Bush (2001)) on the fluid dynamics instability emerged in the thin film rising up the inclined wall. Few works does exist, however, concerning the flow field in the 'tear,' and the flow structure has not been understood at all. In the present study, the authors paid their special attention to this unique, complex flow field of O(1 mm) with deformable surface. The flow pattern and the spatio-temporal particle behavior in the flow were discussed by applying three-dimensional particle tracking velocimetry (3-D PTV).

2 Experiments

Side and front views of the experimental apparatus are shown in Fig. 2. Ethanol-water binary mixture was employed as a test fluid instead of real wines. An open reservoir composed with a rectangular and two triangle sidewalls and a rectangular bottom wall was used as a test section. Those walls were made by Pyrex? glass. The test fluid was settled in this reservoir placed on an inclined optical rail; the present authors focused upon the flow of the 'tears of wine' formed on the rectangular wall (the main plate, hereafter) perpendicular to the optical rail.

Ag-coated hollow spherical glass particles of 10 μm in diameter were used as tracer particles. Its density was 1.4×10^3 kg/m^3. The particles were

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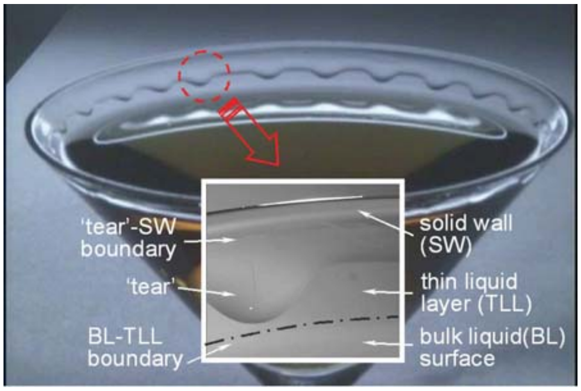

Figure 1: Phenomenon known as 'tears of wine' (left) and a detailed view of a single 'tear' (right). The diameter of the mouse of the glass is of about 50 mm. In a detailed view, a tear is gradually falling down towards the bulk surface of the wine. There exists a thin wine film between the tear and the bulk, which consists of wine rising up against the gravity due to the solutocapillary effect.

placed quietly near the surface of the center part of the tear after the flow was fully developed. The particle motion in the fluid was observed through a cubic splitter fixed beneath the main plate. This observation system enabled us to capture the particle motion with two CCD cameras (768×493 pixels) simultaneously with avoiding any influences of refraction by temporally deforming free surface of the fluid on the glass plate. The particle images were captured at 30 fps with a shutter speed of 1/250 s.

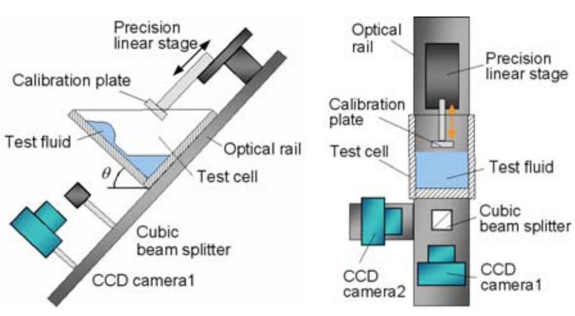

Figure 2: Schematic layout of experimental setup; side (left) and front (right) views. Apparatus is not shown in scale. CCD camera 2 which must be located behind the cubic splitter in the side view is omitted.

Particle motions in successively captured 2-D images by each CCD camera were tracked by applying the modified triple pattern-matching algorithm based on Nishino & Torii (1993). The authors employ a special version of a commercial software tuned for the present system by courtesy of Prof. Koichi Nishino at Yokohama National University, Japan. Three-dimensional velocity field of the particles was reconstructed by the results of the particle tracking process with camera parameters, which were obtained by the camera calibration procedure. This procedure was conducted before/after the experiment using a target plate, on which target marks were engraved. The target plate was traversed in the direction normal to the main plate by use of the precision traversing stage at a certain interval. The image of the target marks was taken at each position by both CCD cameras. The camera parameters to define the camera position, the viewing orientation, the magnification, the lens distortion and the image scale factor were evaluated for each camera with the calibration images. Note that the camera calibration procedure was carried out without the test fluid. The difference of the refraction which arose in obtaining the particle images in the flow field was compensated by applying the Snell's law in the 3-D position reconstruction procedure. Details of the procedures for this technique were described in Nishimura, Ueno, Nishino & Kawamura (2005).

All experiments were carried out under the room temperature condition (25 °C).

3 Results & Discussions

Typical example of the behavior of a 'tear of wine' and the motion of the suspended particles is presented in Fig. 3. The experimental conditions for this case are; the weight percent of ethanol of 40 %, the inclement angle of the main plate of 30°, and the ambient temperature of 24°C. The tear in this figure was detected by another CCD camera placed above the main plate (opposite side to the cubic beam splitter).

The particles were placed at t = t_0 s in this case. An almost horizontal line in each frame corresponds to a boundary line between the risen liq-

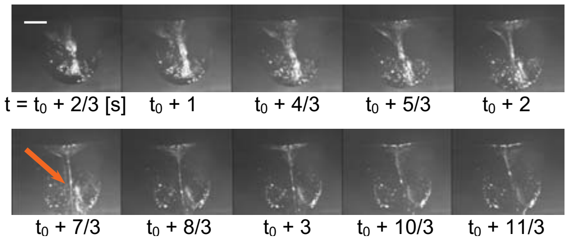

Figure 3: Example of the behaviors of the tear itself and the suspended particle in the tear. These frames were captured by another CCD camera on an opposite side to the cubic beam splitter in Fig. 2. The particles are placed quietly near the surface of the centre part of the tear at t = t_0 s. The front edge of the tear touches the bulk surface, and a strong jet is formed towards the bulk liquid at t = t_0+7/3 in this case. A scale bar in the top left frame corresponds to 1mm.

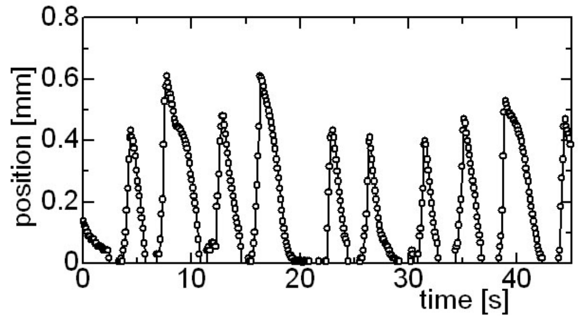

Figure 4: Time series of variation of the tangential position of the front edge of the tear. Position of 0 indicates the position of the bulk surface. Circle plot corresponds to the detected value at each frame.

uid and the main plate surface. The tear gradually falls down on the plate as elapse of time, and the front edge of the tear touches the bulk surface to form a jet (indicated by the arrow) towards the bulk liquid at t = t_0+7/3 s; after the edge of the tear touches the bulk surface, a certain amount of liquid is drained to the bulk. Then the tear rises up on the wall. After a while, the tear gradually falls down toward the bulk again. The particles placed at the almost centre part of falling tear at t = t_0 are split to flow upward and downward in the tear. The particle motion is almost axisymmetry. The particles flowing upward gradually slow down in the vicinity of the boundary between the risen liquid and the main plate surface, and stay beneath the boundary line. The particles around the tear centre flowing downward, on the other hand, slowly move downward as the tear falls down. Some particles are trapped in the region of hydraulic jump and are stuck at their trapped positions. Some particles flowing around the centreline of the tear and not trapped at the edge of the tear are drawn by the strong jet as the edge of the tear touches the bulk, and penetrate into the bulk. Particles located in the side region of the tear follow the vortex flow in the tear until the tear edge touches the bulk surface. After the touch, they decrease their velocity and gradually flow upward.

Typical example of the temporal variation of the tear's front edge position is shown in Fig. 4. Note that this result was obtained in a different run but under the same conditions as shown in Fig. 3. Position of 0 corresponds to the bulk surface. It is interesting to note that the tear rises up to almost the same height as its own tangential size. Let the authors explain the tear's motion with the time series of the tear edge position from the first peak in this figure; after fully rising up the inclined wall, the tear starts to fall down the wall gradually (t > 5 s in the figure) by increasing the amount of the fluid in the tear with the fluid rising up the wall. In falling down the wall, the velocity of the tear's edge is of almost constant. Right after the touch to the bulk surface to expel the fluid from the tear to the bulk, the tear squalls up the wall abruptly because the surface tension keeps pulling up the tear. The tear travels on the inclined wall at an almost constant interval. Careful observation, however, reveals that the interval changes in each up-and-down motion. This is due to exchanges of the fluid among the tears; when another tear next to the present one reach the bulk and expels a part of the fluid inside the tear, the present tear decelerates on the falling way to the bulk as indicated by an arrow in the figure. Strong jet formation in the next tear results in sucking a part of the fluid from the adjacent tears. Such interactions among adjacent tears bring the variation of the interval of the tear.

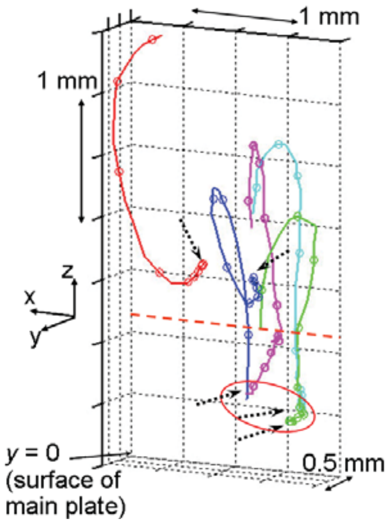

Figure 5: Reconstructed paths of five different particles at different initial locations (dashed arrow) for 1.4 s. Circles are plotted with an interval of 4/15 s. Dashed line indicates the bulk liquid surface. The y direction corresponds to the normal vector of the main plate. Initial positions of two particles in red circle are inside the bulk; the rest at the edge of the tear which is sliding downward to the bulk surface.

The particle motion from just before when the tear's edge touches the bulk surface is reconstructed. Figure 5 indicates an example of reconstructed paths of five different particles inside the tear in a different experimental run from Figs. 2 & 4. Note that their positions at t = t_0 (dashed arrow) correspond to the initial location of those particles in the procedure of position reconstruction, not to the initial positions when the particles are placed. The direction of y in the figure corresponds to the normal vector to the main plate surface. Circles are plotted for the sake of easier tracking of the particle with an interval of 8/30 s extracted from the original data sampled at 30 Hz. Dashed line indicates the bulk liquid surface. Initial positions of three particles in red circle are inside the bulk; the rest at the edge of the tear which is sliding downward to the bulk surface. As the tear edge touches the bulk surface (t = t_0+3/10s), particles near the centre part of the tear are sucked by the jet flow upward. After flowing in the tear for a while (t = t_0+7/10s), the jet toward the bulk is caused. Particles near the side part of (red in the figure) the tear travel toward upper region. The present authors succeeded firstly to reconstruct the spatio-temporal particle behavior in the tear.

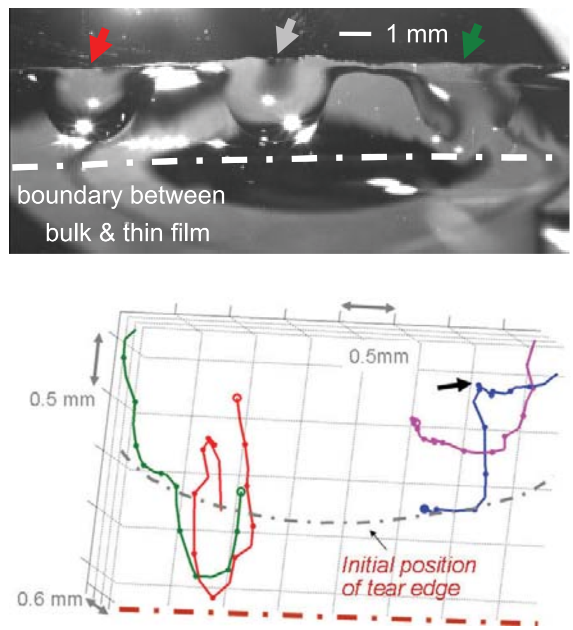

Figure 6: Examples of triple tears (top) and the particle travels towards a neighbor tear (bottom). Intervals between the circles along the trajectories correspond to 2/15 s. Large circle at each trajectory indicates an initial position of the particle when the measuring procedure was started. Thick arrow shows a position where the particle turns its direction of motion towards the neighbor tear.

As indicated in Fig. 4 the interaction among neighbor tears affects the behavior of the tears' tips. Typical example of the triple tears (top) and the particle towards neighbor tear (bottom) are presented in Fig. 6. This particle motion indicates an exchange of the fluid among the tears. Exchange of fluid among adjacent tears leads complex behavior of tear motion as shown in Fig. 7. This figure indicates an example of the phase diagram by considering each edge position in z of three different tears as each coordinate ($z_l(t)$, $z_c(t)$, $z_r(t)$). The orbit never exhibits an ordered

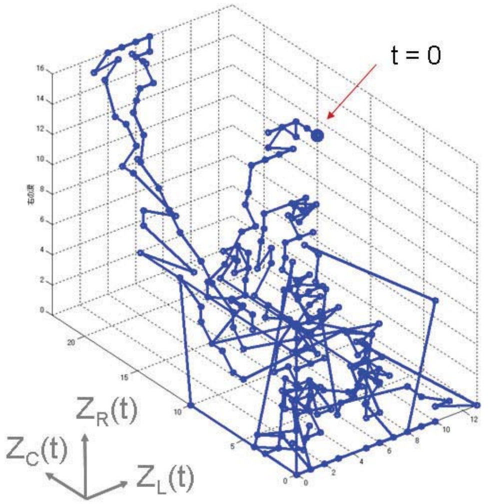

Figure 7: Example of the phase diagram by considering each edge position in z of three different tears as each coordinate (z_l(t), z_c(t), z_r(t)).

motion of the tears.

4 Concluding Remarks

Reconstruction of spatio-temporal particle motion in the flow field known as ‘tears of wine’ due to the solutecapillary effect was conducted by applying the 3-D PTV. Special attention was paid to the particle behavior in unique, complex flow field of O(1 mm) with deformable free surface; especially in the vicinity of the hydraulic jump. The present authors succeeded firstly to reconstruct the particle behavior in the ‘tear of wine.’

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